

M.L. 2019 Project Abstract

For the Period Ending June 30, 2022

PROJECT TITLE: Artificial Den Boxes for Fishers

PROJECT MANAGER: Dr. Michael Joyce

AFFILIATION: U of MN – Duluth, Natural Resources Research Institute

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FUNDING SOURCE: Environment and Natural Resources Trust Fund

LEGAL CITATION: M.L. 2019, First Special Session, Chp. 4, Art. 2, Sec. 2, Subd. 03i

APPROPRIATION AMOUNT: \$190,000

AMOUNT SPENT: \$190,000

AMOUNT REMAINING: \$0

Sound bite of Project Outcomes and Results

Fishers used some den boxes, but it appears fishers find natural cavities to raise young. Den cavity availability alone is likely not causing the fisher population decline. Den boxes were used by many other wildlife species. Installing den boxes could be locally beneficial and increases public involvement with wildlife.

Overall Project Outcome and Results

The fisher population in Minnesota declined by 50% from 2000-2015. Large cavity trees are critical habitat resources that female fishers use to raise kits. Previous research on fishers in Minnesota suggested that lack of large cavity trees could be one factor limiting the fisher population. We evaluated whether den boxes could provide critical habitat for fishers where natural cavities are rare. Our objectives were to build, install, and monitor fisher den boxes to describe use of den boxes by fishers and other wildlife, determine what factors influence whether fishers use den boxes, and to develop guidelines and recommendations for using den boxes to improve habitat. We built and installed 99 den boxes during fall and winter 2019-2020 and captured over 3 million images of wildlife visiting and using den boxes. Fishers visited 41% of den boxes and used 11% of den boxes on 43 different occasions. Use by fishers was lower than in other studies. Low use rates by fishers could indicate cavity availability is not limiting fishers, but additional work is needed to more fully understand why fisher use of den boxes was low and to evaluate other potential causes of the fisher population decline. Habitat suitability at den box sites was not associated with use by fishers. Fisher presence at den boxes increased over time, and fishers should continue to find and use den boxes in the future. Martens, red squirrels, gray squirrels, flying squirrels, and weasels also used den boxes to rest, store food, avoid predators, and care for young. Frequent use of den boxes by other wildlife demonstrates the value of den boxes to wildlife despite low use by fishers. Den box plans and guidelines we developed have allowed many members of the public to build and install their own den boxes, increasing public involvement with wildlife.

Project Results Use and Dissemination

We created den box building instructions and guidelines for den box installation. Throughout the project, we shared these documents directly with 120 members of the public and resource managers who requested information on the project. Project results were disseminated to technical and non-technical audiences through presentations, print and broadcast media, social media posts, and a [Minnesota fisher den box project website](#) we developed. Results are also summarized in a master's thesis. We are currently finalizing a technical report and three manuscripts using data from this project that will be submitted to scientific journals and shared with wildlife managers.



Environment and Natural Resources Trust Fund (ENRTF)

M.L. 2019 ENRTF Work Plan Final Report

Today's Date: August 30, 2022

Final Report

Date of Work Plan Approval: June 5, 2019

Project Completion Date: June 30, 2022

PROJECT TITLE: Artificial Den Boxes for Fishers

Project Manager: Dr. Michael Joyce

Organization: U of MN - Duluth

College/Department/Division: Natural Resources Research Institute

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Location:

Region: Central, Metro, Northwest, Northeast

County Name: Aitkin, Anoka, Becker, Beltrami, Benton, Carlton, Cass, Chisago, Clay, Clearwater, Cook, Crow Wing, Douglas, Hubbard, Isanti, Itasca, Kanabec, Kittson, Koochiching, Lake, Lake of the Woods, Marshall, Mille Lacs, Morrison, Norman, Otter Tail, Pennington, Pine, Polk, Red Lake, Roseau, Sherburne, St. Louis, Stearns, Todd, Wadena, and Washington

Total Project Budget: \$190,000

Amount Spent: \$190,000

Balance: \$0

Legal Citation: M.L. 2019, First Special Session, Chp. 4, Art. 2, Sec. 2, Subd. 03i

Appropriation Language: \$190,000 the first year is from the trust fund to the Board of Regents of the University of Minnesota for the Natural Resources Research Institute in Duluth to build, install, and evaluate den boxes as habitat enhancement for fishers and other cavity-nesting wildlife in managed forests where a lack of large trees may be threatening population survival. The final outcome for the project must include guidelines and best practices for use of den boxes for fisher habitat.

I. PROJECT STATEMENT:

Overview:

The fisher population in Minnesota has declined by about 50% over the past 20 years, and we will deploy den boxes to determine if cavity trees are limiting production of kits. A recent Minnesota DNR study on fishers showed that cavity trees are critically important for female fishers to raise kits. Because large trees with cavities are rare in managed forest landscapes, the DNR study concluded that lack of large trees with cavities may be a limiting resource that contributed to the fisher population decline. Artificial den boxes could help meet the needs of female fishers where natural cavities are rare. If used by fishers, den boxes could enhance fisher habitat and promote population persistence and expansion.

Our project will use what was learned from the DNR project to address whether cavity trees are a limiting resource for fishers in Minnesota and evaluate artificial den boxes as a potential solution if cavity trees are limiting. We will build and install at least 60 nest boxes in Minnesota, monitor use by fishers and other wildlife species, and determine what factors influence whether fishers use boxes. We will also use existing data from the DNR fisher study to identify areas with low fisher habitat suitability where den boxes could potentially be used to enhance fisher habitat. Finally, we will develop instructions on how to build artificial den boxes for fishers and best management guidelines for their use and disseminate our instructions and guidelines to wildlife managers, foresters, private landowners, trappers, and other members of the public interested in enhancing fisher habitat. This project will generate the knowledge necessary to develop strategic plans for fisher habitat management and could lead to a novel method for monitoring the fisher population in Minnesota.

Project Statement:

Fishers are mid-sized carnivores that live in the forested region of Minnesota. Minnesota DNR data shows that the fisher population has declined by about 50% over the last 20 years (see figure on map page).

The fisher population decline has not received as much attention as the northeast Minnesota moose population decline has, even though populations are about half of what they were 20 years ago.

In response to the fisher population decline the DNR conducted a research project from 2008-2015 to learn more about fisher ecology in Minnesota. The DNR project found that for fishers in Minnesota:

- Females raise their kits in cavities of large-diameter trees (see map page)
- Cavity trees are critically important for reproduction
- Large cavity trees are relatively scarce in managed forests

The DNR study identified denning habitat as a possible limiting factor, and concluded that a lack of suitable cavities may have contributed to the fisher population decline. Our project will use what was learned from the DNR project to address whether cavity trees are a limiting resource for fishers in Minnesota and evaluate artificial den boxes as a potential solution if cavity trees are limiting.

Fishers are the largest animal in Minnesota that requires cavities to raise their young. Large diameter trees with cavities big enough to hold fishers take years to grow. In managed forests, trees may be harvested before any tree has time to develop a heart-rot cavity, and existing cavity trees may be lost during logging or wind storms. Fishers do not use leave trees in openings in harvested forests, instead using trees in interior forests.

Artificial den boxes could help meet the needs of female fishers where natural cavities are rare. Den boxes could be used to enhance fisher habitat and promote population persistence in managed landscapes. Placing a den box on the edge of a harvested forest where prey species occur might actually create new fisher habitat. Signs that this project will benefit Minnesota wildlife include:

1. **Wildlife managers have observed fishers using wood duck nest boxes in Minnesota**
2. **Fishers have raised litters in artificial den boxes in western Canada**
3. **Den box use by fishers could be an indicator of whether cavity trees are a limiting resource**
4. **Den boxes could provide an additional method for monitoring fisher populations in Minnesota**
5. **Private landowners have requested information on building den boxes for fishers from the DNR**

At this stage, we know den boxes are used by fishers, but we do not know what influences whether individual den boxes are used or whether installing den boxes where large cavity trees are rare will allow fishers to better use areas that lack natural cavities. Results of this project could be used by wildlife managers, private landowners, trappers, and other concerned citizens to promote fisher population expansion. In the future, den boxes could be used for public engagement and might even be a way for citizen-scientists to help monitor fisher populations in Minnesota.

We have coordinated with the DNR to develop this proposal, and one of the real strengths of this project is it will help determine how artificial den boxes can be a tool for fisher habitat management. We will use den boxes to further evaluate whether cavity trees are a limiting resource that contributed to recent fisher population declines in Minnesota. The specific goals of this project on fisher artificial denning boxes are to:

- 1. Build and install at least 60 artificial den boxes in Minnesota.**
- 2. Monitor visitation and use of den boxes by fishers and other wildlife.**
- 3. Determine what factors influence use of den boxes by fishers.**
- 4. Develop guidelines and best management practices for use of artificial den boxes for fishers.**
- 5. Identify areas with low habitat suitability as potential sites for future fisher habitat management.**

II. OVERALL PROJECT STATUS UPDATES:

First Update March 1, 2020

During fall and winter 2019-2020 we built and installed 80 fisher den boxes for this project and worked with partners to build and install an additional 31 den boxes (123 total den boxes, including the 12 boxes from our pilot study). We will need to monitor wildlife use of boxes for another year and a half to fully address our objectives to document use of den boxes by fishers and other wildlife, determine what factors influence whether fishers use den boxes, identify priority areas for future den box management, and develop best management guidelines for using fisher den boxes. Nonetheless, monitoring of den boxes is ongoing and we are on track to complete this project on time based on the proposed timeline in our research addendum. Through our first several months of den box monitoring, we have obtained ~150,000 pictures from remote cameras at den boxes and documented fishers at 9% of den boxes. This rate of use is higher than what was documented in a previous fisher den box project in British Columbia. We also documented frequent use of den boxes by squirrels and mice and other wildlife visiting our boxes such as bears, raccoons, owls, and moose. We have received immense public interest in this project, and have been able to disseminate information about the project directly to over 60 individuals (largely members of the public) and to various technical and general audiences through presentations and print media.

AMENDMENT REQUEST March 4, 2020

We are requesting funds be shifted from two supply line budget items to two other supply line budgets.

- Den boxes supply line budget would increase by \$2,949 to a revised budget of \$7,749
- Camera supply line budget would decrease by \$3,450 to a revised budget of \$10,200
- Shop use supply line budget would decrease by \$130 to a revised budget of \$0
- Field supplies supply line budget would increase by \$631 to a revised budget of \$2,051

These changes are being requested because the box cost was higher than anticipated after some design modifications we made following our pilot study, because we found existing cameras from project partners that we could use instead of purchasing 75 cameras, and because lithium batteries used for the cameras were slightly more expensive than we budgeted for. The NRRI wood shop also waived the fee to use the space, so we wanted to re-allocate this money to the Field supplies supply line to help cover cost of lithium batteries.

Amendment Approved by LCCMR 3/9/2020

Second Update September 1, 2020

During spring and summer 2020 we monitored use of 80 fisher den boxes built and installed for this project and worked with partners to monitor an additional 19 den boxes. We will need to monitor wildlife use of boxes for about another 9-10 months to fully address our objectives to document use of den boxes by fishers and other wildlife, determine what factors influence whether fishers use den boxes, identify priority areas for future den box management, and develop best management guidelines for using fisher den boxes. Nonetheless, monitoring of den boxes is ongoing and we are on track to complete this project on time based on the proposed timeline in our research addendum. Through our first nine months of den box monitoring, we have obtained >1 million pictures from remote cameras at den boxes and documented fishers at 17% of den boxes. This rate of use is higher than what was documented in a previous fisher den box project in British Columbia during their first year. We also documented frequent use of den boxes by squirrels and mice and other wildlife visiting our boxes such as bears, raccoons, owls, and moose. We have received immense public interest in this project, and have been able to disseminate information about the project directly to 69 individuals (largely members of the public) and to various technical and general audiences through presentations and print media.

AMENDMENT REQUEST August 24, 2020

We are requesting funds be shifted from two supply line budget items to two other supply line budgets.

- Field supplies supply line budget would increase by \$781 to a revised budget of \$2,832.
- Personnel budget line would decrease by \$781 to a revised budget of \$151,219.

These changes are being requested because the cost of lithium batteries to power remote cameras was higher than anticipated. This money could be re-allocated from the personnel budget without affecting our ability to complete this study as proposed.

Amendment Approved by LCCMR 9/9/2020

Third Update March 1, 2021

During fall 2020 and winter 2021 we monitored use of 80 fisher den boxes built and installed for this project and worked with partners to monitor an additional 19 den boxes. We will need to monitor wildlife use of boxes for about another 3-3.5 months to fully address our objectives to document use of den boxes by fishers and other wildlife, determine what factors influence whether fishers use den boxes, identify priority areas for future den box management, and develop best management guidelines for using fisher den boxes. Nonetheless, monitoring of den boxes is ongoing. Through the first 15 months of den box monitoring, we have obtained >1.6 million pictures from remote cameras at den boxes and documented 5 species of wildlife using the boxes: fishers, martens, flying squirrels, red squirrels, and gray squirrels. Fisher detections at den boxes begin to increase late last summer, and fishers have been documented at nearly 30% of den boxes. It is taking longer than expected to analyze the large volume of pictures from den boxes, and we are asking for a 6 month no cost extension to allow more time to finish project analyses. We continue to receive immense interest in the project from the media and members of the public and have been able to disseminate information about the project directly to 78 individuals (largely members of the public) and to various technical and general audiences through presentations and print media.

AMENDMENT REQUEST February 24, 2021

We have collected over 1.6 million pictures from remote cameras at den boxes, and we estimate that we will collect an additional 300,000 to 500,000 pictures during the remainder of our field monitoring, ending May 2021. This volume of pictures is higher than we anticipated, and it is taking longer than we expected to analyze the picture data. The extra time required to process these images is due in part to the University's hiring freeze related to the COVID-19 pandemic. Consequently, it will take longer than anticipated to complete the data analyses as proposed with existing personnel. We are requesting an additional year to allow more time to analyze the pictures we have collected and complete all project components. Project outcomes in the Activity 1 table have been adjusted to meet this longer timeline. The remaining funding is sufficient to complete the project as described in this work plan.

Additionally, we are requesting funds be shifted from the personnel budget line to the travel budget line.

- Travel budget line would increase by \$2,000 to a revised budget of \$20,000.
- Personnel budget line would decrease by \$2,000 to a revised budget of \$149,219.

These changes are being requested because the cost of travel to complete den box monitoring was slightly higher than anticipated. This money could be re-allocated from the personnel budget without affecting our ability to complete this study as proposed.

Budget amendment approved by LCCMR 03/08/2021

Project Extension Amendment request dependent on legislative and LCCMR action 03/08/2021—withdrawn 3/11/2021

After additional review, LCCMR staff noted that the appropriation for this project extended to June 30, 2022 and an administrative extension to match the work plan end date to the appropriation end data was sufficient. To that end, the COVID-related legislative extension is withdrawn, and the administrative extension is approved as of 3/11/2021

Fourth Update September 2021

During spring and early summer 2021 we completed monitoring on most of the 80 fisher den boxes built and installed for this project and worked with partners to monitor an additional 19 den boxes. We have several boxes that need one final monitoring visit. We have been analyzing data throughout summer 2021 to address our objectives to document use of den boxes by fishers and other wildlife, determine what factors influence whether fishers use den boxes, identify priority areas for future den box management, and develop best management guidelines for using fisher den boxes. Through the first 21 months of den box monitoring, we have obtained >2.1 million pictures from remote cameras at den boxes and documented 5 species of wildlife using the boxes: fishers, martens, flying squirrels, red squirrels, and gray squirrels. Fisher use of den boxes has continued to increase over the last 6-10 months, and fishers have been documented at nearly 30% of den boxes. It is taking longer than expected to analyze the large volume of pictures from den boxes, but we are making progress developing a machine learning algorithm to help us analyze images more efficiently. We continue to receive immense interest in the project from the media and members of the public and have been able to disseminate information about the project directly to 90 individuals (largely members of the public) and to various technical and general audiences through presentations and print media.

AMENDMENT REQUEST September 1, 2021

We are requesting funds be shifted from two budget lines to the travel budget line.

- Field Supplies budget line would decrease by \$36 to a revised budget of \$2,796.
- Personnel budget line would decrease by \$764 to a revisited budget of \$148,455.
- Travel budget line would increase by \$800 to a revised budget of \$20,800.

These changes are being requested because the cost of travel to complete den box monitoring was slightly higher than anticipated. This change to travel funding will be sufficient to cover two days of field visits, which will allow us to complete all field work on this project. Additionally, we have no need to purchase any more field supplies. Thus, this money could be re-allocated from the field supplies and personnel budget lines without affecting our ability to complete this study as proposed.

Budget amendment approved by LCCMR 09/13/2021

Fifth Update March 2022

During fall and early winter 2021 we completed monitoring on all of the 80 fisher den boxes built and installed for this project and worked with partners to monitor an additional 19 den boxes. We have been exploring machine learning approaches for analyzing our trail camera data, summarized habitat data, and conducted GIS analyses to address our objectives to document use of den boxes by fishers and other wildlife, determine what factors influence whether fishers use den boxes, identify priority areas for future den box management, and develop best management guidelines for using fisher den boxes. Throughout our den box monitoring, we have

obtained >2.4 million pictures from remote cameras at den boxes and documented 5 species of wildlife using the boxes: fishers, martens, flying squirrels, red squirrels, and gray squirrels. Fisher use of den boxes has continued to increase over time, and fishers have been documented at nearly 35% of den boxes. It is taking longer than expected to analyze the large volume of pictures from den boxes, and machine learning approaches have yielded mixed results. We continue to receive immense interest in the project from the media and members of the public and have been able to disseminate information about the project directly to over 110 individuals (largely members of the public) and to various technical and general audiences through presentations and print media. We are on track to complete this project by the end date.

AMENDMENT REQUEST March 1, 2022

We are requesting funds be shifted from the personnel budget line to the travel budget line.

- Personnel budget line would decrease by \$26 to a revised budget of \$148,429.
- Travel budget line would increase by \$26 to a revised budget of \$20,826.

These changes are being requested to zero-out the travel budget line because travel costs were slightly higher than anticipated when we made our last amendment request. There will be no further travel costs charged to this project. All future expenses will be for personnel time to complete the analysis and reports, and this small reduction in the personnel budget line will not affect our ability to complete this project.

Amendment approved by LCCMR 3/11/22

AMENDMENT REQUEST September 1, 2022

We are requesting funds be shifted as follows.

- Personnel budget line would decrease by \$148 to a revised budget of \$148,281.
- Travel budget line would decrease by \$2 to a revised budget of \$20,824.
- Field supply budget line would increase by \$150 to a revised budget of \$2,946.

These minor changes are being requested to zero-out all categories at the end of the project. All work on this project has been completed at the time of this request.

Amendment approved by LCCMR 11/18/22

Final report June 30-August 15, 2022

The fisher population in Minnesota declined by 50% from 2000-2015. Large cavity trees are critical habitat resources that female fishers use to raise kits. Previous research on fishers in Minnesota suggested that lack of large cavity trees could be one factor limiting the fisher population. We evaluated whether den boxes could provide critical habitat for fishers where natural cavities are rare. Our objectives were to build, install, and monitor fisher den boxes to describe use of den boxes by fishers and other wildlife, determine what factors influence whether fishers use den boxes, and develop guidelines and recommendations for using den boxes to improve habitat. We built and installed 99 den boxes during fall and winter 2019-2020 and captured over 3 million images of wildlife visiting and using den boxes. Fishers visited 41% of den boxes and used 11% of den boxes on 43 different occasions. Use by fishers was lower than in other studies. Low use rates by fishers could indicate cavity availability is not limiting fishers, but additional work is needed to more fully understand why fisher use of den boxes was low and to evaluate other potential causes of the fisher population decline. Habitat suitability at den box sites was not associated with use by fishers. Fisher presence at den boxes increased over time, and fishers should continue to find and use den boxes in the future. Martens, red squirrels, gray squirrels, flying squirrels, and weasels also used den boxes to rest, store food, avoid predators, and care for young. Frequent use of den boxes by other wildlife demonstrates the value of den boxes to wildlife despite low use by fishers. Den box plans and guidelines we developed have allowed many members of the public to build and install their own den boxes, increasing public involvement with wildlife.

III. PROJECT ACTIVITIES AND OUTCOMES:

ACTIVITY 1 Title: Determine visitation and use of artificial den boxes by fishers and other wildlife species

Description: We will build and install at least 60 den boxes in two study areas where previous fisher research has taken place. Den boxes will be installed in different forest types and ages. We will use remote cameras and field-visits to monitor visitation and use by fishers. We will visit den boxes during the breeding season to document reproduction in den boxes using an inspection camera mounted on a pole to determine whether kits are present. If kits are present, we will obtain a litter count. We will also monitor visitation and use by other wildlife species, including other cavity-dependent species such as squirrels, wood ducks, and other cavity-nesting birds. Lastly, we will use existing data from the DNR fisher study to identify areas with low fisher habitat suitability where den boxes could potentially be used to enhance fisher habitat and prioritize areas for future habitat management.

ACTIVITY 1 ENRTF BUDGET: \$190,000

Outcome	Completion Date
1. Installation of artificial den boxes	November 2019
2. Determine visitation and use of den boxes by fishers and other wildlife species	June 2021
3. Identify factors influencing use of den boxes by fishers	July 2021
4. Identify and prioritize areas with low habitat suitability where den boxes could potentially be used to enhance fisher habitat in the future	December 2021
5. Develop and disseminate instructions on how to build artificial den boxes for fishers and best management guidelines for their use	December 2021

First Update March 1, 2020

We built and installed 80 fisher den boxes during fall 2019 (40 per each of two study areas). We modified our den box design following our pilot study, which increased den box cost but will increase the longevity of the boxes. In addition to the boxes built using ENRTF funding, we worked with partners to build and install additional den boxes that will expand the project sample size to 123 total den boxes. All 123 den boxes will be monitored for two years or more to address outcomes 2, 3, and 4. Partners include UPM/Blandin, Leech Lake Band of Ojibwe, Cloquet Forestry Center, Carlton County land department, and Hubachek Wilderness Research Center. These additional boxes were built and will be monitored using non-ENRTF funding.

We have currently obtained ~150,000 images from remote cameras at den boxes, and we anticipate that we will collect 1 to 1.5 million images over this two-year project. We have analyzed preliminary data collected while monitoring these boxes to determine visitation and use of den boxes by fishers and other wildlife, but we defer a complete assessment of results for outcomes 2 and 3 until we have completed two years of monitoring and analyzed the data. Preliminary results are that fishers have visited or used 9% of the den boxes within 2 months of box installation. We have also documented numerous other wildlife using the boxes, including flying squirrels, red squirrels, gray squirrels, mice, and birds. We have also documented bears, raccoons, porcupines, and moose visiting and investigating den boxes, but these animals are too big to enter the boxes.

We have begun analyzing LiDAR data and evaluating other geospatial forest inventory data to map fisher habitat suitability to prioritize areas for future den box deployments but will require results for outcome 3 to complete outcome 4. Progress on outcome 5 is discussed in section IV. Dissemination.

Second Update September 1, 2020

We have currently obtained ~1,035,000 images from remote cameras at den boxes, and we anticipate that we will collect 2 to 2.5 million images over this two-year project. Currently, we have analyzed >220,000 (~21%) of all

pictures collected. Due to the high volume of pictures, we are exploring automated methods for sorting pictures that rely on machine learning.

We have analyzed preliminary data collected while monitoring these boxes to determine visitation and use of den boxes by fishers and other wildlife, but we defer a complete assessment of results for outcomes 2 and 3 until we have completed two years of monitoring and analyzed the data. Preliminary results are that fishers have visited or used 17% of the den boxes to date. We have also documented numerous other species of wildlife using the boxes, including flying squirrels, red squirrels, gray squirrels, mice, and birds. We have also documented bears, raccoons, porcupines, and moose visiting and investigating den boxes, but these animals are too big to enter the boxes. Mammals have visited or used 93% of den boxes, while birds have visited or used 66% of den boxes.

We have measured fisher habitat suitability at 69 out of 80 fisher den boxes to determine how habitat suitability influences whether fishers and other wildlife visit or use individual den boxes (outcome 3). We will finish measuring habitat suitability at remaining boxes by 9/1/2020.

We have begun analyzing LiDAR data and evaluating other geospatial forest inventory data to map fisher habitat suitability to prioritize areas for future den box deployments but will require results for outcome 3 to complete outcome 4. Progress on outcome 5 is discussed in section IV. Dissemination.

Third Update March 1, 2021

We have currently obtained ~1.6 million images from remote cameras at den boxes, and we anticipate that we will collect 2 to 2.5 million images over this two-year project. Currently, we have analyzed >340,000 (~22%) of all pictures collected. Due to the high volume of pictures and inefficiencies of manual photo analysis, we are testing a new automated method using machine learning for sorting pictures. The method can analyze ~2,000 pictures per minute. Testing the new method should be completed in late March 2021.

We have analyzed preliminary data collected while monitoring these boxes to determine visitation and use of den boxes by fishers and other wildlife and measured fisher habitat quality at all den boxes, but we defer a complete assessment of results for outcomes 2 and 3 until we have completed two years of monitoring and analyzed the data. Preliminary results are that fishers have visited or used almost 30% of the den boxes to date. We have also documented numerous other species of wildlife using the boxes, including flying squirrels, red squirrels, gray squirrels, and martens. We have also documented bears, raccoons, porcupines, and moose visiting and investigating den boxes, but these animals are too big to enter the boxes. Mammals have visited or used 93% of den boxes, while birds have visited or used 70% of den boxes.

We have measured fisher habitat suitability at all 80 fisher den boxes to determine how habitat suitability influences whether fishers and other wildlife visit or use individual den boxes (outcome 3). Habitat data has been entered, and we have begun analyzing habitat suitability at boxes where fishers have currently been detected.

We have begun analyzing LiDAR data and evaluating other geospatial forest inventory data to map fisher habitat suitability to prioritize areas for future den box deployments but will require results for outcome 3 to complete outcome 4. Progress on outcome 5 is discussed in section IV. Dissemination.

Fourth Update September 2021

We have currently obtained ~2.1 million images from remote cameras at den boxes, and field monitoring of boxes is nearly completed. Currently, we have analyzed >450,000 (~21%) of all pictures collected. Due to the high volume of pictures and inefficiencies of manual photo analysis, we are testing a new automated method using machine learning for sorting pictures. The method can analyze up to 2,000 pictures per minute. Testing is ongoing, but machine learning is expected to be incorporated into our processing workflow in early September.

We have analyzed preliminary data collected while monitoring these boxes to determine visitation and use of den boxes by fishers and other wildlife and measured fisher habitat quality at all den boxes, but we defer a complete assessment of results for outcomes 2 and 3 until we have completed analysis of trail camera images. Preliminary results are that fishers have visited or used about 30% of the den boxes to date. We have also documented numerous other species of wildlife using the boxes, including flying squirrels, red squirrels, gray squirrels, and martens. We have also documented bears, raccoons, porcupines, and moose visiting and investigating den boxes, but these animals are too big to enter the boxes. Mammals have visited or used 93% of den boxes, while birds have visited or used 70% of den boxes. We have also seen drastic differences in detections of wildlife species between our two primary study areas. We anticipate completing Outcome 2 in early- to mid-Fall 2021 and Outcome 3 in mid- to late-Fall 2021.

We have measured fisher habitat suitability at all 80 fisher den boxes to determine how habitat suitability influences whether fishers and other wildlife visit or use individual den boxes (outcome 3). Habitat data has been entered, and we have begun analyzing habitat suitability at boxes where fishers have currently been detected. We are waiting to finish Outcome 2 before finalizing this analysis.

We have begun analyzing LiDAR data and evaluating other geospatial forest inventory data to map fisher habitat suitability to prioritize areas for future den box deployments and we have made preliminary GIS maps of fisher habitat suitability across our study areas. However, it will require results for outcome 3 to complete outcome 4. Progress on outcome 5 is discussed in section IV. Dissemination.

Fifth Update March 1, 2022

We have obtained >2.5 million images from remote cameras at den boxes, and field monitoring of boxes has been completed. Currently, we have analyzed >500,000 (~20%) of all pictures collected. Due to the high volume of pictures and inefficiencies of manual photo analysis, we tested a machine learning method for automated image analysis. The original method we tested did not work, but we have tested another method that is ~85% accurate at identifying images with fishers. We are working to automate processing for most of the remaining images that have not been analyzed.

We have analyzed preliminary data collected while monitoring these boxes to determine visitation and use of den boxes by fishers and other wildlife and measured fisher habitat quality at all den boxes, but we defer a complete assessment of results for outcomes 2 and 3 until we have completed analysis of trail camera images. We continue to see fishers visiting boxes where they were not detected in previous years.

We measured fisher habitat suitability at all 80 fisher den boxes to determine how habitat suitability influences whether fishers and other wildlife visit or use individual den boxes (outcome 3). We have calculated habitat suitability indices for all den boxes and have begun analyzing habitat suitability at boxes where fishers have currently been detected. We are waiting to finish Outcome 2 before finalizing this analysis.

We continue to analyze LiDAR and other geospatial data to support outcome 4, but must finalize outcome 3 in order to complete outcome 4. Progress on outcome 5 is discussed in section IV. Dissemination.

Final report June 30-August 15, 2022

Outcome 1. Installation of fisher den boxes

We built and installed 80 fisher den boxes during fall 2019 (40 per each of two study areas). We also installed 7 den boxes during our pilot study and worked with the following partners to install additional den boxes: Carlton County Land Department (4 boxes), Cloquet Forestry Center (4 boxes), Hubachek Wilderness Research Center (2 boxes), Leech Lake Band of Ojibwe (12 boxes). Results summarized here are from all of these den boxes except those installed by Leech Lake Band of Ojibwe. We modified our den box design following our pilot study, which

increased den box cost but will increase the longevity of the boxes. Den boxes built and installed with partners were built and monitored using non-ENRTF funding.

Outcome 2. Determine visitation and use of den boxes by fishers and other wildlife species

We obtained >3.3 million images from remote cameras at den boxes. Due to the high volume of pictures and inefficiencies of manual photo analysis, we tested several machine learning approaches for automated image analysis. After full evaluation, none of the methods we tested were accurate enough for automated image analysis. We fully analyzed 30% of images and analyzed a subsample of the remaining images. We also used other monitoring methods (glue strips for hair, temperature loggers inside boxes, inspection of the box interior for depressions or other sign of use by fishers, martens, or squirrels) to ensure that we detected all uses of den boxes by fishers. Some den box visits by species such as squirrels, martens, and birds were missed in our analysis methods.

We defined a camera event as any image or series of images triggered by the same animal or non-animal cause with no gaps greater than 30 minutes. We defined a visit as the presence of any animal at or near the den box. If animals were detected in the site surrounding the box but did not visit the actual box, we did not consider these occurrences to be visits. We defined a use as an animal entering and remaining inside the den box for at least 30 minutes or use of the den box for another discrete purpose (e.g., storing food). We analyzed over 30,000 events.

We documented 14 species of mammals visiting den boxes: fisher, American marten, southern flying squirrel, northern flying squirrel, red squirrel, gray squirrel, short-tailed weasel, deer mice or white-footed mice, porcupine, black bear, raccoon, eastern chipmunk, least chipmunk, moose, unidentified bats, and bobcat. We also detected deer, wolf, badger, gray fox, and hare in the vicinity of den boxes. We consider moose visitors because they generally inspected the boxes when detected at sites. We also had 36 bird species visit den boxes, but no birds were documented using den boxes. Fishers were detected at 41% of den boxes, while flying squirrels, red squirrels, and birds were detected at almost all den boxes. Throughout the study, every box had at least one species visit it.

Only a subset of animals detected at den boxes were documented using them. We documented fishers using 11 den boxes (~11%) on 43 separate occasions. The most frequent use of den boxes by fishers was for resting. Female fishers also used den boxes to rest with their kits, to select mates (i.e., female fishers were inside the box while males wanted to mate, and females used their secure position to elect not to mate), and to cache prey they had killed. The number of uses at each box was variable. Three boxes used by fishers were used a single time, three boxes were used twice, 1 box was used 3 times, 2 boxes were used 6 times by fishers, 1 box was used 8 times, and 1 box was used 11 times. The box used 11 times had a total of 80 fisher camera events. Three additional boxes had 40 or more fisher camera events, while most boxes had fewer fisher camera events.

When we started this project, we thought that den sites might be limiting fisher reproduction. If there are not enough natural den site cavities, then female fishers would use den boxes to raise kits. Frequent use of several den boxes indicates fishers were able to find the den boxes and supports past research showing fishers are willing to use den boxes. However, we found relatively low rates of fishers visiting and using our den boxes both in terms of number of boxes with fishers detected and relatively few revisits for many of the boxes where fishers were detected. This result is similar to a previous fisher den box study in British Columbia: they documented fishers visiting or using 48% of den boxes within the first 3 years, while we found fishers visiting or using 41% of den boxes within 2.5 years of monitoring. One difference between that study and ours is that they documented fishers raising kits in 15% of their boxes (10 total reproductive uses), while we only documented kits at 3% of our boxes and all of these were in mid-summer through early fall when kits were already semi-independent. Previous studies on closely-related martens also generally documented higher rates of martens visiting and using boxes than the rates we documented for fishers. There are a few possible explanations for the relatively low use rates and lack of use for raising dependent kits.

First, presence but low rates of revisits or uses could suggest that sufficient natural cavities are available. The fact that a female fisher brought her kits to one of our den boxes two years in a row but did not use the box to give birth or care for kits suggests that at least where that box was located, other options are available and preferred. Given the recent decrease in the fisher population and resulting lower fisher density, unoccupied habitat could be available, and fishers should be able to avoid areas where cavities are locally rare. Data from our ongoing ENRTF-funded study on bobcat and fisher interactions will help further evaluate this explanation. By deploying GPS collars on female fishers near den boxes, we can determine where they are giving birth and raising kits instead of den boxes.

A second potential explanation is that fishers may not have been present at every site where den boxes were installed. We used past radio-telemetry and harvest data to select general areas for den box deployment that had historical records of fisher presence, but we could not verify fisher presence in each stand we installed a den box in. Several observations are consistent with this explanation, at least for a subset of the boxes. First, fishers were not detected at over half of the boxes. This includes from camera data, and from searches we did for fisher sign (e.g., snow tracks) while driving throughout the study area, walking to den boxes, and while at the den box site. Second, the Minnesota DNR experienced low capture rates in some of the areas we installed den boxes towards the end of their fisher study. Third, boxes with a single fisher visit or use across the roughly 2.5-year monitoring period could represent transient and not resident fishers. It is likely that both explanations probably contributed to the low use of artificial den boxes by female fishers with kits in Minnesota.

The low use rates by fishers have several important implications that need to be further evaluated. First, they provide evidence that cavity availability may not be the primary factor limiting the fisher population in Minnesota. One other factor that could cause a decline in the fisher population that was identified by the Minnesota DNR was predation by bobcats. We are currently evaluating bobcat and fisher interactions through a separate ENRTF-funded project. Cavity availability may be high in habitats bobcats use, increasing predation risk for female fishers, and the bobcat and fisher study should help us evaluate that. Second, although our results support the hypothesis that natural cavity availability is not limiting the fisher population in Minnesota, we did not measure cavity availability. Recently, methods have been developed that could be used to quantify and map cavity availability, and future research could use these methods to evaluate cavity availability more directly. We intend to pursue future funding to address this important knowledge gap.

Martens used den boxes on 25 occasions. Martens used den boxes primarily for resting but also used den boxes to cache prey. Red, gray, and flying squirrels frequently used boxes, but camera images were not always sufficient to determine whether boxes were being visited or used. Flying squirrels used many den boxes as communal winter rest sites and for storing mushrooms to eat later. Red squirrels built nests, mated on den boxes, cached cones inside boxes, and used den boxes to raise juveniles at least one time. Gray squirrels rested in boxes, used a box to escape predators, and used the box to raise at least one litter. A weasel cached prey inside one den box on 4 different occasions. Den boxes were also used by wasps and bumblebees to build nests, although we did not quantify how many times this happened.

The frequent use of den boxes by species other than fishers demonstrates that fisher den boxes also provided habitat for many Minnesota wildlife species. Thus, the boxes installed by this project helped protect, conserve, and enhance Minnesota's wildlife.

Outcome 3. Identify factors influencing use of den boxes by fishers

We evaluated factors influencing use of den boxes by fishers in several ways: 1) we compared presence of fishers and other wildlife at boxes in our two main study areas to determine whether use was dependent on location; 2) we determined how long it took fishers and other wildlife to first visit and use den boxes to evaluate how time since deployment affects den box use; and 3) we determined whether fisher habitat suitability influenced whether fishers visited or used den boxes to evaluate where den boxes should be installed to have maximum impact.

Wildlife presence at den boxes varied between our two main study areas. Fishers were detected at more than twice as many boxes in the Superior National Forest, with 7x more events at that study area. Martens were only detected at boxes in the Superior NF, while gray squirrels were basically only detected at boxes in the Chippewa NF. In both cases, this is a reflection of where martens and gray squirrels live in the state. Red squirrels were detected at more boxes in the Superior NF, while weasels and flying squirrels were detected at similar numbers of boxes in each study area. It is not clear whether the fisher results are due to their being fewer fishers in the Chippewa National Forest study area, but anecdotal data suggests this might be the case. A previous fisher den box study in British Columbia also found variable rates of fisher presence at boxes they deployed in different areas, so these results are not completely unexpected.

Fishers took much longer to be documented at den boxes than other animals that used den boxes. The fastest fisher detection occurred 21 days after box installation, while the time to fastest detection was less than a week for the other 4 species. The longer time to detection for fishers is probably due to the larger space requirement and lower density of fishers relative to these smaller species. Given the slow and approximately linear trend for fishers using den boxes, we expect fishers will continue to find and use den boxes in the future. These results are also important to communicate how quickly fishers may find and use boxes with members of the public that are interested in building and installing den boxes.

We installed boxes using a stratified random approach that allowed us to install den boxes in a range of forest conditions with different suitability to fishers. This design allowed us to explicitly test the effect of habitat suitability on fisher use of boxes. If fishers preferred boxes, we expected to find high use rates regardless of habitat quality. If cavity trees were limiting, we either expected use to be higher in high quality habitat to reflect where fishers would be most likely to find and use boxes or for boxes to get the most use if they were in stands that had other habitat resources such as prey but that lacked natural cavities. We did not put any boxes in non-habitat where fishers would have been unlikely to be present or to use boxes.

We did not find a strong pattern between habitat suitability and whether fishers visited or used den boxes. Boxes fishers visited and used had a slightly higher median suitability score than those they were not detected, but fishers also visited and used boxes in stands with low estimated suitability. Presence of fishers across a range of suitability values is not likely due to fishers moving into lower quality habitat due to an abundance of fishers. Instead, it could indicate that the habitat suitability index we used does not represent suitability of an area for female fishers to rest or raise kits.

Outcome 4. Identify and prioritize areas with low habitat suitability where den boxes could potentially be used to enhance fisher habitat in the future

During this project, we developed methods to map habitat suitability for fishers so that we could identify and prioritize areas where den boxes could potentially be used to enhance fisher habitat. However, low use rates of den boxes by fishers and lack of a predictable relationship between habitat suitability and fisher use of den boxes have prevented us from being able to objectively identify and prioritize areas where fisher den boxes could be used to enhance fisher habitat. Future work aimed at directly quantifying and mapping cavity availability could provide a better basis for establishing areas where fisher den boxes could be used to increase cavity availability.

Outcome 5. Develop and disseminate instructions on how to build artificial den boxes for fishers and best management guidelines for their use

We created den box building instructions and worked with Carlton County Land Department to create recommendations on how and where to install fisher den boxes. These documents are attached to this report. We have disseminated these documents to 120 members of the public and wildlife managers throughout the project, and these documents will soon be posted on our website so they can be disseminated into the future.

Additional outcomes

This project also resulted in several un-anticipated outcomes that added value to the project beyond what we expected when we began the project. These outcomes are summarized below.

Temperature logger data from den boxes was used by M.S. student Taylor Velandar for his thesis (Mechanisms underlying American marten winter rest site selection across the Western Great Lakes Region, 2022) on the thermal ecology of den boxes and cavities. Taylor used the temperature data to develop a mathematical model to predict cavity and den box internal temperatures and used the model to evaluate how temperature influenced American marten winter rest site selection and energetics. These measurements showed that the foam insulation we put in the den boxes helped make temperature more stable and comparable to temperatures in natural tree cavities. The model also allowed us to compare the thermal environment provided by den boxes to that provided by natural tree cavities fishers previously used in Minnesota. We are preparing to submit a manuscript describing his mathematical model to a scientific journal.

We also used temperature logger data to develop a novel method to use temperature loggers to monitor use of den boxes. The method works because fishers and other animals using den boxes alter the temperature within den boxes in predictable ways. The method identified all instances when fishers used den boxes. These results suggest that temperature loggers could be a cost-effective alternative to using trail cameras to monitor den boxes, although using them with trail cameras could enhance the type of data practitioners could gain from den box monitoring. We are preparing a manuscript describing this method that will be submitted to a scientific journal.

The lack of a pattern between habitat suitability at den boxes and use by fishers may suggest that the habitat suitability index we used does not adequately represent fisher reproductive habitat in Minnesota. This is a topic that current Ph.D. student Michael McMahon will explore as part of his thesis project, building on the results of this project.

This project also documented high rates of den box use by squirrel species, including 3 species of squirrels using the same box at different times. Additionally, the camera data we collected during this project allowed us to identify several areas where northern and southern flying squirrels were both present. There is regional concern about the conservation status of northern flying squirrels. The scientific literature suggests that these two species may not use the same stands, so this finding was unexpected and may have implications for flying squirrel density and interactions. We have used these sightings to inform a new proposal we recently submitted for ENRTF funding.

IV. DISSEMINATION:

Description: We will create a website to distribute information to the public, but this will be done after the project starts. The website will be modelled after other websites we maintain (e.g., www.nrri.umn.edu/moose or www.nrri.umn.edu/bats).

We will also use our results to develop and disseminate instructions on how to build artificial den boxes for fishers and best management guidelines for their use. These instructions and guidelines will be intended for use by wildlife managers, foresters, private landowners, trappers, and other members of the public interested in enhancing fisher habitat. We will share our instructions and guidelines directly with these groups and also post it on our website.

In addition, we will present project results at local and regional scientific meetings and prepare and submit papers for publication in peer-reviewed journals.

We will likely have periodic contact with print and broadcast media. These contacts will be documented as they occur.

The Minnesota Environment and Natural Resources Trust Fund (ENRTF) will be acknowledged through use of the trust fund logo or attribution language on project print and electronic media, publications, signage, and other communications per the [ENRTF Acknowledgement Guidelines](#).

First Update March 1, 2020

We are in the process of creating a website to distribute information to the public, but have not launched the website yet due to ongoing work on other aspects of the project (i.e., deploying and monitoring den boxes). We anticipate the website will be live by May 2020 based on current progress.

We will not create best management guidelines for using den boxes until the end of this project, once our full results are available. We have developed instructions on how to build den boxes for internal use and will be creating den box plans during summer 2020 to disseminate to those interested in building their own artificial den boxes for fishers.

We have received requests from 61 different members of the public and wildlife managers wishing to build their own den boxes since January 2019. Requests have mostly come from individuals living in Minnesota (49), Michigan (2), and Wisconsin (5), but we have also received requests from individuals living in Pennsylvania (2) and Maine (3).

To date, we have given 5 presentations on this project at scientific meetings and 6 presentations to non-technical audiences. Presentations have focused on project background, objectives, and preliminary results. Presentations were given at the following scientific meetings: American Society of Mammalogists (July 2019), Cloquet Forestry Center Forestry and Wildlife Research Review (January 2020), Midwest Fish and Wildlife Conference (January 2020), Minnesota Chapter of The Wildlife Society (February 2020), Minnesota Chapter of the Society for American Foresters (February 2020). Presentations to non-technical audiences were given to the following groups: Legislative delegation visit to NRRI (August 2019), Cloquet Forestry Center Open House (August 2019), Forest Resource Association's visit to NRRI (September 2019), CFANS visit to NRRI (December 2019), Lake Superior College Ecology Class (December 2019), Duluth Chapter of the Izaak Walton League (February 2020). We have not prepared any technical reports or papers as results are still preliminary.

There were 6 articles written about the project by print media:

- "UMD researchers build news dens for forest fishers: a shortage of big trees to nest in may be one factor in the big decline in Minnesota's fisher population over the last decade", Duluth News Tribune, October 27, 2019.
- "Den boxes could help falling numbers of fishers in Minnesota's north woods", Quetico Superior Wilderness News, October 29, 2019.
- "Den boxes provide nesting habitat for fishers", Natural Resources Research Institute News, November 1, 2019.
- "A future for fisher? Research to test potential of artificial nest boxes for reversing the decline in fisher numbers", Timberjay, November 21, 2019.
- "Fisher den box project", 1854 Treaty Authority Newsletter, December 2019.
- "9 wins for Minnesota in 2019", Minnesota Lottery Website, December 16, 2019.

Second Update September 1, 2020

We have created a draft version of a website to distribute information to the public, and it is in the final stages of review and revision before the website goes live. We anticipate the website will be live by September 2020 based on current progress. Additionally, we have shared 2 brief project updates with the public via social media. These posts have generated a lot of interest: the first post was “liked” over 100 times and shared >40 times. The second post was “liked” over 120 times and shared >10 times.

We will not create best management guidelines for using den boxes until the end of this project, once our full results are available. We have developed instructions on how to build den boxes for internal use. We are currently in the process of creating den box plans to disseminate to those interested in building their own artificial den boxes for fishers. We anticipate these instructions being completed during Fall 2020.

We have received requests from 69 different members of the public and wildlife managers wishing to build their own den boxes since January 2019. This includes an additional 8 requests since the last progress update. Requests received since the last update have come from individuals living in Minnesota (6), Michigan (2).

To date, we have given 6 presentations on this project at scientific meetings and 8 presentations to non-technical audiences. Presentations have focused on project background, objectives, and preliminary results. Presentations were given at the following scientific meetings: American Society of Mammalogists (July 2019), Cloquet Forestry Center Forestry and Wildlife Research Review (January 2020), Midwest Fish and Wildlife Conference (January 2020), Minnesota Chapter of The Wildlife Society (February 2020), Minnesota Chapter of the Society for American Foresters (February 2020), Minnesota Forest Resources Partnership (June 2020, virtual meeting). Presentations to non-technical audiences were given to the following groups: Legislative delegation visit to NRRI (August 2019), Cloquet Forestry Center Open House (August 2019), Forest Resource Association’s visit to NRRI (September 2019), CFANS visit to NRRI (December 2019), Lake Superior College Ecology Class (December 2019), Duluth Chapter of the Izaak Walton League (February 2020), Fond du Lac Tribal Community College (March 2020), Sugarloaf Cove Nature Center (July 2020). We have not prepared any technical reports or papers as results are still preliminary.

There were 6 articles written about the project by print media, all of which are listed in the last progress update. Additionally, Dr. Michael Joyce was interviewed by Rob Drieslein for Outdoor News Radio about fishers, including the ongoing fisher den box project.

Third Update March 1, 2021

We have created a draft version of a website to distribute information to the public, and it is in the final stages of review and revision before the website goes live. We have not finalized the website yet to allow us to spend more time analyzing trail camera images, but the website is scheduled to be finalized in early March 2021. Additionally, we have shared 4 brief project updates with the public via social media. These posts have generated a lot of interest, as discussed in the Second Update on September 1, 2020.

We will not create best management guidelines for using den boxes until the end of this project, once our full results are available. We have developed instructions on how to build den boxes for internal use. We are currently in the process of creating den box plans to disseminate to those interested in building their own artificial den boxes for fishers. Those plans are in the final stages of editing and should be finished in March 2021.

We have received requests from 78 different members of the public and wildlife managers wishing to build their own den boxes since January 2019. This includes an additional 9 requests since the last progress update. Requests received since the last update have come from individuals living in Minnesota (7), Michigan (1), and Maine (1).

To date, we have given 7 presentations on this project at scientific meetings and 8 presentations to non-technical audiences. Presentations have focused on project background, objectives, and preliminary results. Presentations given at the scientific meetings since the last update include UW Stevens Point student chapter of The Wildlife Society (October 2020, virtual). No presentations were given to non-technical audiences since the last update. We have not prepared any technical reports or papers as results are still preliminary, but we are currently working on a paper on den box monitoring methods.

Since the last update, Dr. Michael Joyce was interviewed live on the radio as part of KUMD's Green Visions program on November 18, 2020. Additionally, Dr. Michael Joyce was recently interviewed by Javier Serna for Outdoor News (article published in the February 19 issue) and Bob Timmons with the Star Tribune (article planned for March 2021). All interviews and articles were related to this project.

Fourth Update September 2021

We have not yet finalized our draft website. We have delayed finalizing this website again to allow us to spend more time analyzing trail camera images, but we plan to finalize it in October or November 2021.

We will not create best management guidelines for using den boxes until the end of this project, once our full results are available, but we have begun to create draft versions of those guidelines. We have developed instructions on how to build den boxes for internal use. We are currently in the process of creating den box plans to disseminate to those interested in building their own artificial den boxes for fishers. Those plans will be shared with the public via our website when it goes live later this fall.

We have received requests from 90 different members of the public and wildlife managers wishing to build their own den boxes since January 2019. This includes an additional 10 requests since the last progress update. Requests received since the last update have come from individuals living in Minnesota (9) or Denmark (1). The individual from Denmark, where fishers do not live, found a news article on the project online and wanted info so that he could make den boxes for European pine martens. Dr. Joyce shared information on pine marten den boxes along with information about the fisher den box project.

To date, we have given 9 presentations on this project at scientific meetings and 11 presentations to non-technical audiences. Presentations have focused on project background, objectives, and preliminary results. Presentations given at the scientific meetings since the last update include two presentations given at the American Society of Mammalogists' annual meeting (June 2021, virtual), one focusing on den box monitoring techniques and a second focusing on the thermal environment within den boxes and tree cavities. Presentations given to non-technical audiences since the last update include a presentation given to the Ely Field Naturalists' Tuesday Group (April 2021, virtual), the Whitewater State Park HOP program (June 2021, virtual), and a guest lecture given to undergraduate students at the University of Minnesota (August 2021, in person). We have not prepared any technical reports or papers as results are still preliminary, but we are currently working on a paper on den box monitoring methods.

Since the last update, the Star Tribune article by Bob Timmons that was highlighted during the last update was published on March 4, 2021. Dr. Joyce also worked with project partner Dr. Roger Powell to write an article about the project that was published in the Ely Summer Times (Summer 2021 issue).

Fifth Update March 2022

We have not yet finalized our draft website. We have delayed finalizing this website again to allow us to spend more time analyzing trail camera images. We planned to finalize our website in October/November 2021, but NRRI was creating a new website at that time, so we delayed our launch to take advantage of the new website structure to host our den box web site. We are currently working with our Marketing and Communication staff to migrate our draft website to the new format.

The status of our efforts to create management guidelines and building instructions are unchanged from the last update. We will finalize these after other work is complete, but we have made progress on draft versions.

We have received requests from 116 different members of the public or wildlife managers wishing to build their own den boxes since January 2019. Requests received since the project started have come from individuals living in Minnesota (91), Wisconsin (7), Maine (4), Michigan (4), New York (3), Pennsylvania (3), Canada (1), Denmark (1), the United Kingdom (1), and from unknown location (1).

To date, we have given 10 presentations on this project at scientific meetings and 12 presentations to non-technical audiences. Presentations have focused on project background, objectives, and preliminary results. Presentations given at scientific meetings since the last update include one presentation given to the Great Lakes Native American Fish and Wildlife Society meeting in late September 2021 in Manistee, Michigan (conference travel was paid for by NRRI and not with ENRTF funding since the travel was out of state). Presentations given to non-technical audiences since the last update include a presentation given to the West Metro Chapter of the Minnesota Master Naturalists. We have not prepared any technical reports or papers as results are still preliminary, but we are currently working on a paper on den box monitoring methods. Additionally, a manuscript using the temperature data we collected is in the final stages of preparation before submission to a scientific journal.

Final report June 30-August 15, 2022

Throughout the project, we have heard from many individuals expressing interest in the project and requesting information on how to build and install fisher den boxes. We have disseminated den box building plans and preliminary guidelines to at least 120 different individuals, including members of the public and wildlife managers wishing to build their own den boxes. Most of these requests have come from people living in Minnesota (95), but we have also heard from people living in Wisconsin (7), Maine (4), Michigan (4), New York (3), Pennsylvania (3), Canada (1), Denmark (1), the United Kingdom (1), and from an unknown location (1).

As noted above, we developed den box building plans and guidelines for their installation. We have created a [website for the Minnesota fisher den box project](#) to help disseminate project information, results, images, den box building plans and guidelines for installing den boxes. We will continue to maintain the website and updated it as needed (e.g., as publications and our technical report are finished).

We have given numerous presentations about the project at both scientific conferences and presentations to non-technical audiences. Presentations have focused on project background, objectives, and preliminary results. The following is a complete list of the 13 presentations given at scientific conferences during this project:

- Evaluating artificial den boxes as a habitat management tool for fishers in Minnesota, Minnesota Chapter of the Wildlife Society Annual Meeting, February 2019
- Modeling thermal properties of fisher reproductive dens: implications for artificial den boxes, American Society of Mammalogists Annual Meeting, June 2019
- Evaluating artificial den boxes as a habitat management tool for fishers in Minnesota, Presentation for Chippewa National Forest and Minnesota DNR, June 2019
- Minnesota fisher den box project update, Forestry and Wildlife Research Review, January 2020
- Improving forest management to conserve habitat for cavity-obligate wildlife: fishers as a case study, Midwest Fish and Wildlife Meeting, January 2020
- Minnesota fisher den box project update, Minnesota Chapter of the Wildlife Society Annual Meeting, February 2020
- Minnesota fisher den box project update, Minnesota Chapter of the Society of American Foresters, February 2020

- Minnesota fisher den box project: preliminary results, Minnesota Forest Resources Partnership, Spring 2020
- Fisher research project update, presentation to National Forest Biologists, February 2021
- Using temperature loggers to monitor use of artificial den boxes by fishers, American Society of Mammalogists Annual Meeting (virtual), June 2021
- A dynamic thermal model for predicting internal temperature of tree cavities and den boxes, American Society of Mammalogists Annual Meeting (virtual), June 2021
- Evaluating fisher den boxes as a habitat management tool, Great Lakes Native American Fish and Wildlife Society meeting, September 2021
- Fisher research project update, presentation to National Forest Biologists, March 2022

The following is a complete list of the 12 presentations given to non-technical audiences during this project:

- Minnesota fisher den box project, Minnesota Legislators and University of Minnesota Leadership, August 2019
- Wildlife research program overview, Forest Resources Association, October 2019
- Fishers in Minnesota: history, status, and current research. Lake Superior College ecology students, December 2019
- Fishers in Minnesota: past, present, and future. W.J. McCabe Chapter (Duluth) of the Izaak Walton League, February 2020
- Fishers in Minnesota, University for Seniors Program, University of Minnesota Duluth, February 2020
- Minnesota Ojib (fisher) den box project, Fond Du Lac Tribal Community College, March 2020
- Fishers in Minnesota: history, status, and current research. Sugarloaf Cover Nature Center, July 2020
- Fishers: cryptic carnivores of the Northwoods, UW-Stevens Point student chapter of The Wildlife Society, October 2020
- Fisher ecology and ongoing fisher research in Minnesota, Ely Field Naturalists Tuesday Group, February 2021
- Fishers in Minnesota: history, status, ecology, and ongoing research. Whitewater State Park HOP program, June 2021
- A tale of two predators: bobcat and fisher history, ecology, and ongoing research. West Metro Master Naturalists, February 2022 [also discussed ongoing ENRTF-funded study on bobcat and fisher habitat use and interactions]
- Fishers in Minnesota: history, status, and ongoing research. Mississippi River Valley Audubon Center, June 2022

We will give additional presentations following the completion of this project.

Masters graduate student Taylor Velander (UM-Duluth, Integrated BioSciences Graduate Program) completed his thesis using data from the den box project in July 2022. We are also in the process of completing one technical report and 3 manuscripts to be published in peer-reviewed journals from this project. The thesis, report, and manuscripts in progress are listed below:

- T.B. Velander. 2022. Mechanisms underlying American marten (*Martes americana*) winter rest site selection. M.S. Thesis, University of Minnesota Duluth, Integrated BioSciences Graduate Program. [Used fisher den box data to develop and test a mathematical model to predict temperature within natural cavities and den boxes]

- M.J. Joyce, M.C. McMahon, T.B. Velander, R.A. Moen. Use of den boxes by fishers and other wildlife. NRRI Technical Report. *Expected completion fall 2022.*
- T.B. Velander, M.J. Joyce, R.L. Sanders, A.K. Kujawa, P.W. Keenlance, R.A. Moen. A dynamic thermal model for predicting internal temperature of tree cavities and den boxes. *To be submitted to Ecological Modeling October 2022.*
- M.J. Joyce, T.B. Velander, M.C. McMahon, M. Swingen, R. Olesiak, T. Roerick, S. Mortenson, R.A. Moen. Factors influencing use of den boxes by fishers and other wildlife. *To be submitted to Wildlife Biology.*
- T.B. Velander, M.J. Joyce, M.C. McMahon, R.A. Moen. Using temperature loggers to monitor occupancy of den boxes. *To be submitted to Wildlife Society Bulletin.*

The Minnesota fisher den box project was featured in the print and broadcast media 11 times:

- Field Notes: New dens for fishers. Minnesota Conservation Volunteer, Jan-Feb 2019 issue.
- UMD researchers build new dens for forest fishers: a shortage of big trees to nest in may be one factor in the big decline in Minnesota's fisher population over the last decade. Duluth News Tribune, 10/27/2019 (Sunday Outdoors Section).
- Den boxes could help falling numbers of fishers in Minnesota's north woods. Quetico Superior Wilderness News, 10/29/2019.
- Den boxes provide nesting habitat for fishers. NRRI Newsletter, 11/1/2019.
- A future for fisher? Research to test potential of artificial nest boxes for reversing the decline in fisher numbers. Timberjay, 11/21/2019.
- Fisher den box project. 1854 Treaty Authority Newsletter, December 2019.
- 9 wins for Minnesota in 2019. Minnesota Lottery, December 2019.
- Fisher den boxes: helping rebuild populations...and a whole lot of monkey business. KUMD Green Visions Radio interview and article, November 2020.
- Trail cams keep tabs on researchers' fisher denning boxes. Outdoor News Minnesota, February 2021.
- Researchers deploy den boxes as possible tool to aid mysterious fishers. Star Tribune, 3/4/2021.
- Will den boxes help fishers? Ely Summer Times, Summer 2021.

Additionally, we have used NRRI's social media to share images of various wildlife at den boxes. We have acknowledged the ENRTF in accordance with guidelines during dissemination activities.

V. ADDITIONAL BUDGET INFORMATION:

A. Personnel and Capital Expenditures

Explanation of Capital Expenditures Greater Than \$5,000: N/A

Explanation of Use of Classified Staff: N/A

Total Number of Full-time Equivalents (FTE) Directly Funded with this ENRTF Appropriation:

Enter Total Estimated Personnel Hours for entire duration of project: 4,827	Divide total personnel hours by 2,080 hours in 1 yr = TOTAL FTE: 2.32
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Total Number of Full-time Equivalents (FTE) Estimated to Be Funded through Contracts with this ENRTF Appropriation:

Enter Total Estimated Contract Personnel Hours for entire duration of project: N/A	Divide total contract hours by 2,080 hours in 1 yr = TOTAL FTE: N/A
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VI. PROJECT PARTNERS:

A. Partners outside of project manager's organization receiving ENRTF funding N/A

B. Partners outside of project manager's organization NOT receiving ENRTF funding

Dr. John Erb (MN DNR) will provide input and in-kind support on this project, with intent to use results to help inform fisher habitat management recommendations.

VII. LONG-TERM- IMPLEMENTATION AND FUNDING:

This proposal is part of a larger effort to understand fisher and pine marten ecology in Minnesota. We envision this as a project that builds off the results of the DNR fisher project and develops techniques to enhance fisher habitat. This project will generate the knowledge necessary to develop strategic plans for fisher habitat management. Den boxes will last many years and could provide a new method for monitoring fisher populations in Minnesota.

We will use our results to develop guidelines for use of fisher den boxes, including instructions on how to build boxes. These guidelines and instructions are meant to be used by wildlife managers, private land owners, trappers and other members of the public interested in enhancing fisher habitat. The Land Resources Department in Carlton County has already deployed one fisher den box that we built after hearing about our project, and they have already indicated that they would like to deploy more boxes in 2018. We expect interest by other agencies and the public as well.

This project could lead to a future opportunity for public engagement through a large-scale citizen-science project. Using what we learn in this project, we could establish a network of fisher den boxes that could be maintained and monitored by citizens to collect samples and data to contribute to fisher habitat and population monitoring efforts.

VIII. REPORTING REQUIREMENTS:

- Project status update reports will be submitted March 1 and September 1 each year of the project
- A final report and associated products will be submitted between June 30 and August 15, 2022

IX. SEE ADDITIONAL WORK PLAN COMPONENTS:

A. Budget Spreadsheet: See Attachment A

B. Visual Component or Map: See Attachment B

C. Parcel List Spreadsheet: N/A

D. Acquisition, Easements, and Restoration Requirements: N/A

E. Research Addendum: Research Addendum will be submitted by September 14, 2018.

Attachment A:

Environment and Natural Resources Trust Fund

M.L. 2019 Budget Spreadsheet

Legal Citation: M.L. 2019, First Special Session, Chp. 4, Art. 2, Sec. 2, Subd. 03i

Project Manager: Dr. Michael Joyce

Project Title: Artificial Den Boxes for Fishers

Organization: U of MN - Duluth

Project Budget: \$190,000

Project Length and Completion Date: 3 Years, June 30, 2022

Today's Date: Septembert 1, 2022



ENVIRONMENT AND NATURAL RESOURCES TRUST FUND BUDGET	Revised Budget 9/1/2022	Amount Spent	Balance
BUDGET ITEM			
Personnel (Wages and Benefits)	\$ 148,281	\$ 148,281	\$ 0
Michael Joyce, Principal Investigator: ~~\$94,059~~ \$94,033 (fringe rate 36%); ~57% FTE each year for 2			
Ron Moen, Project Partner: \$3,173 (fringe rate 33.5%); 1% FTE each year for 2 years			
Technician: \$29,755 (fringe rate 27.2%); ~27.5% FTE each year for 2 years			
Undergraduate Research Assistant: \$14,476 (100% salary); 29% FTE each year for 2 years			
Temp/Casual: \$1,000 (fringe rate 8.2%); ~1% FTE			
Graduate Student: \$5,992 (fringe rate 16.1%), 25% FTE each summer for 2 years			
Equipment/Tools/Supplies			
Den boxes (80 @ \$97/box): includes materials for building and hanging boxes and temperature loggers	\$ 7,749	\$ 7,749	\$ -
Cameras (60 @ \$170). Additional cameras will come from project partners	\$ 10,200	\$ 10,200	\$ -
Field supplies (e.g., batteries for cameras, bug dope, gps, GoPro and pole for den box checks)	\$ 2,946	\$ 2,946	\$ (0)
Travel expenses in Minnesota			
Travel for fieldwork, including mileage (75%) and lodging for technician, researcher, and undergraduate research assistant. Mileage will be reimbursed at \$0.58/mile (U of M rate). Lodging is estimated between \$90 and \$110 per night, less if camping is possible. Some trips will involve longer-distance travel and require overnight expenses (camping or motel) and food expenses.	\$ 20,824	\$ 20,824	\$ 0
COLUMN TOTAL	\$ 190,000	\$ 190,000	\$ -

OTHER FUNDS CONTRIBUTED TO THE PROJECT	Status (secured or pending)		Spent	Balance
Non-State:		\$ -	\$ -	\$ -
State:		\$ -	\$ -	\$ -
In kind:		\$ -	\$ -	\$ -
Unrecovered indirect: 54% on total direct costs (\$190,000 base)	Secured	\$ 102,600		\$ 102,600
In-kind support from DNR biologist John Erb: 80 hours of in-kind support over 2 years	Secured	\$ 4,500	\$ 4,500	\$ -
HOB0 temperature loggers (30 @ \$60)	Secured	\$ 1,800	\$ 1,800	\$ -

PAST AND CURRENT ENRTF APPROPRIATIONS	Amount legally obligated but not yet spent		Spent	Balance
Current appropriation:			\$ -	\$ -
Past appropriations:			\$ -	\$ -

Natural Resources Research Institute

UNIVERSITY OF MINNESOTA DULUTH
Driven to Discover

NRRI TECHNICAL REPORT

FISHER DEN BOX BUILDING PLANS



Submitted by:

Dr. Michael Joyce, Ph.D., and Dr. Ron Moen, Ph.D.

Date: August 2022

Report Number: NRRI/TR-2022/14

Funding:

Environment and Natural Resources Trust Fund
M.L. 2019, First Special Session, Chp. 4, Art. 2, Sec. 2, Subd. 03i

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Recommended Citation:

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Introduction

The design for this fisher den box is based on a design that has been used for fishers in British Columbia (Davis 2016). We made minor design modifications as described in this manual, for example we used screws instead of nails in all construction. Almost 100 of these boxes were deployed in northern Minnesota, with several boxes used by fishers (M. Joyce, 2022, Final Report, Environment and Natural Resources Trust Fund project M.L. 2019, First Special Session, Chp. 4, Art. 2, Sec. 2, Subd. 03i).

The thermal characteristics of several prototype den boxes were reported in Velandar (2022). Temperatures inside of the den boxes with $\frac{3}{4}$ " extruded polystyrene insulation were more stable and less extreme than temperatures in uninsulated den boxes relative to daily fluctuations in ambient temperature.

Den Box Dimensions and Parts List

The external dimensions of the box are $14\frac{1}{2}$ " x $14\frac{1}{2}$ " x $31\frac{1}{2}$ " and the internal dimensions are $10\frac{3}{4}$ " x $10\frac{3}{4}$ " x $29\frac{1}{2}$ ", and a completed box weights about 55 pounds. The box can be made with one sheet of plywood, 2 1x2s, a half of a sheet of extruded polystyrene insulation, and screws. Wood and foam are cut to size (Table 1). The sheet of $\frac{1}{2}$ " plywood is cut into 13 pieces (Fig. 2). One of the 1x2s is cut into 3 $31\frac{1}{2}$ " pieces, the other is cut into smaller pieces (Table 1). For insulation, $\frac{3}{4}$ " extruded polystyrene should be used, cut as indicated in Table 1. One additional cut is needed in the extruded polystyrene for one of the four sides for part 3C.

Table 1. List of parts needed for the fisher den box.

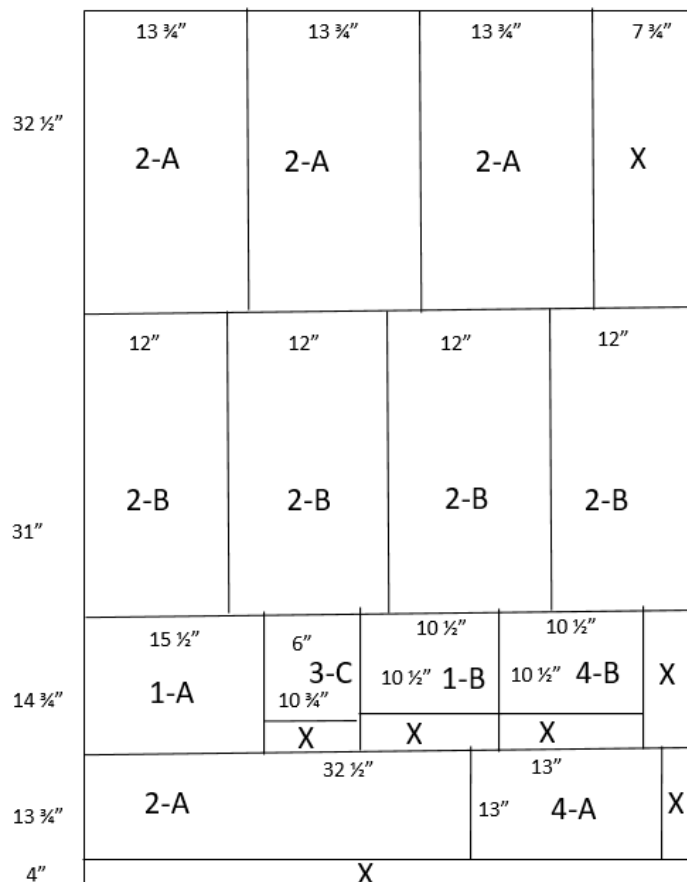
Part	Type	Material	Size	Quantity
1-A	Top (external)	$\frac{1}{2}$ " plywood	$14\frac{3}{4}$ " x $15\frac{1}{2}$ "	1
1-B	Top (internal)	$\frac{1}{2}$ " plywood	$10\frac{1}{2}$ " x $10\frac{1}{2}$ "	1
2-A	Sides (external)	$\frac{1}{2}$ " plywood	$13\frac{3}{4}$ " x $32\frac{1}{2}$ "	4
2-B	Sides (internal)	$\frac{1}{2}$ " plywood	12 " x $31\frac{1}{2}$ "	4
2-C	Support	1x2	$31\frac{1}{2}$ "	3
2-D	Support	1x2	$20\frac{3}{4}$ "	1
2-E	Support	1x2	$10\frac{1}{2}$ "	4
2-F	Sides	$\frac{3}{4}$ " styrofoam	12 " x $31\frac{1}{2}$ "	4
3-C	Opening	$\frac{3}{4}$ " plywood	6 " x $10\frac{3}{4}$ "	1
4-A	Bottom (external)	$\frac{1}{2}$ " plywood	13 " x 13 "	1
4-B	Bottom (internal)	$\frac{1}{2}$ " plywood	$10\frac{1}{2}$ " x $10\frac{1}{2}$ "	1
4-F	Bottom	$\frac{3}{4}$ " styrofoam	$10\frac{1}{2}$ " x $10\frac{1}{2}$ "	1
5-A	Opening	1x2	6 "	2
5-B	Opening	1x2	4 "	2

Depending on what is available, alternative materials could be substituted. For example, the design calls for $\frac{1}{2}$ " plywood, but $\frac{3}{4}$ " plywood, solid wood, or a plastic material could be substituted for the top of the box (1-A). Metal roofing should not be used because fishers and other species use the top of the box to rest. Similarly, $\frac{3}{4}$ " plywood could be substituted for the wood core near the box opening (3-C). We used

$\frac{1}{2}$ ", $\frac{5}{8}$ ", and $\frac{3}{4}$ " plywood in testing den box designs, some of which was treated plywood. Untreated plywood should have a preservative finish such as water-based deck stain applied to the exterior of the den box.

All pieces needed for the den box can be cut from 1 sheet of plywood (Fig. 1). One of the 2-A pieces needs to have an opening cut into it in the upper left as described below. The opening is 3" x 4" (7.6 cm x 10.2 cm).

Figure 1. Cutting pattern for den box if only 1 sheet of plywood is used. Letter-Number combinations (e.g., 2-A) refer to the parts list (Table 1). X indicates the piece is not used.

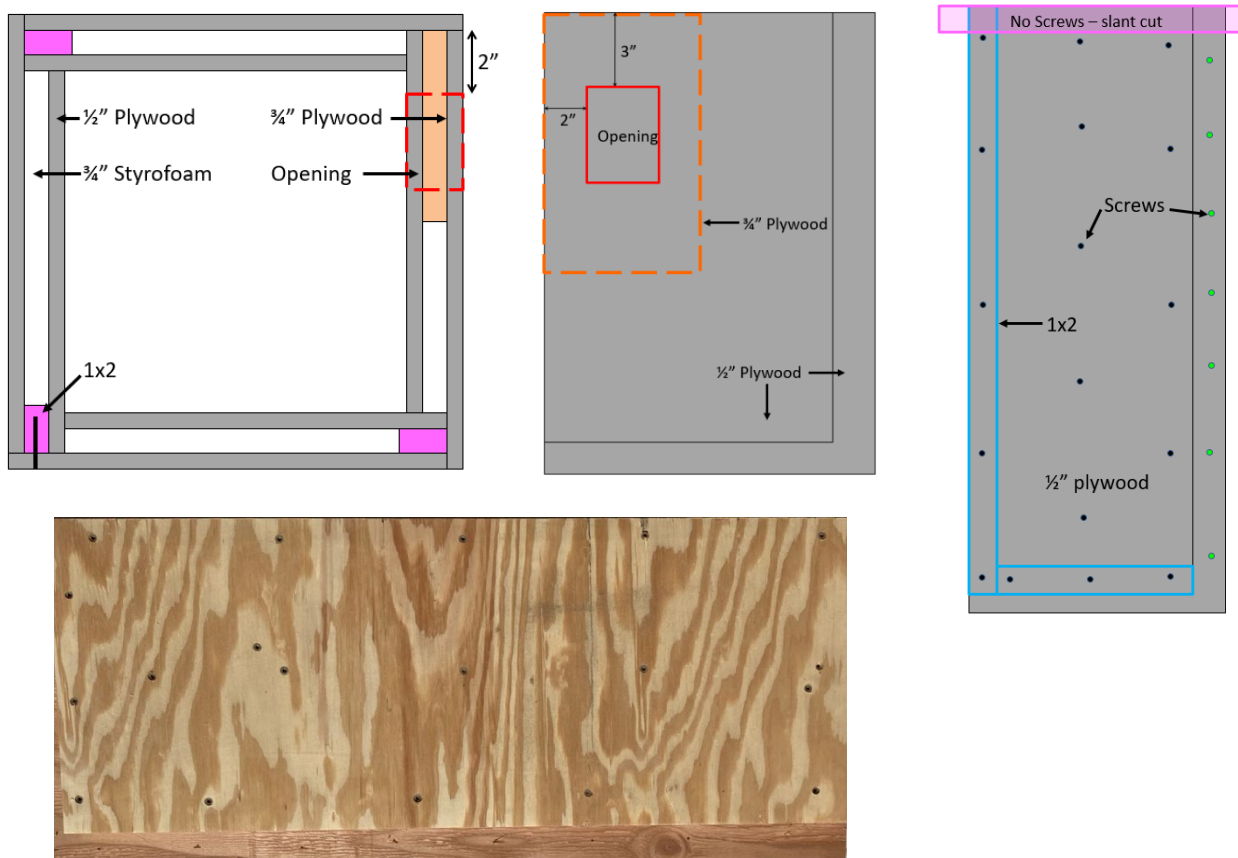


Side Construction and Arrangement

The parts used for constructing the sides are 2-A, 2-B, 2-C (3), 2-D, 2-F, and 3-C. The 1x2s were a design modification to increase strength of the joint, with screws going into the 1x2s in addition to the $\frac{1}{2}$ " thick plywood. The diagram on the left in Fig. 4 shows how the sides are attached to each other.

One of the sides (2-A) should have an opening cut into it as shown in the diagram in the middle in Fig. 2. The $\frac{3}{4}$ " plywood (3-C) is needed, or dimensional lumber can be used, to match the thickness of the extruded polystyrene insulation where the opening is cut. The opening must also be cut in part 3-C.

Figure 2. Top view of sides and side view of side of den box with opening. Top view and side view are not to same scale. The picture shows the inside of one of the sides (2-B), with screws going through the foam insulation (2-F) and attaching to the outside side (2-A).



Screws are used to sandwich the Styrofoam between the two pieces of plywood. The first screw should be 1" from the bottom of piece 2-B/2-F, centered on the 1x2 in the side panel. Additional screws should be put every 4 inches until 8 total screws have been placed. No screws should be within 1 $\frac{3}{8}$ " of the top where the slope cut will be made. Approximate screw locations are shown in Fig. 4, schematically and in the photograph are screw locations for one den box side. A template can be made for drilling holes to attach side panels to each other.

It should take 17 screws per side panel and an additional 8 screws for the 1x2s, or a total of about 100 1 5/8" screws for assembling the sides. Screw length might need to be changed if different wood thicknesses are used.

The roof is cut at a 5-degree slant, and there is a slight roof overhang on the lowest part of the slant. The door opening should be next to the highest part of the roof. The roof angle can be cut after the den box is assembled, or it can be cut on individual pieces. The additional 1x2s at the opening are installed as an additional thicker barrier, because different species will chew on openings in some of the den boxes that are deployed.

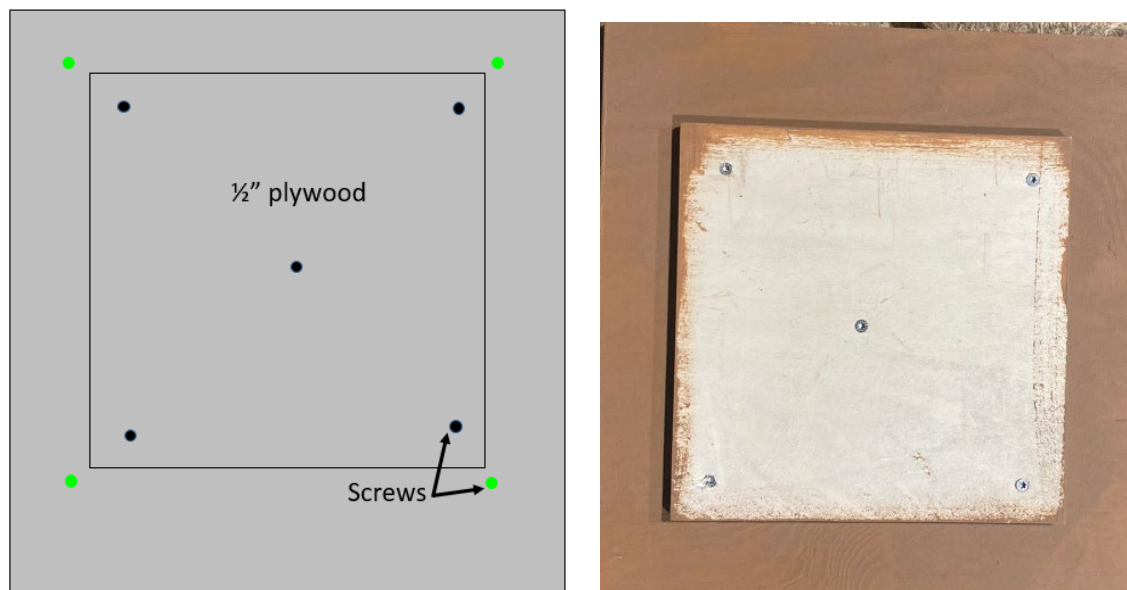
Figure 3. Side view of den box with opening, showing the additional 1x2 pieces that are screwed into the opening. An unfinished opening is shown in the middle picture, and fishers at a den box are shown in the right picture.



Top and Bottom Construction and Arrangement

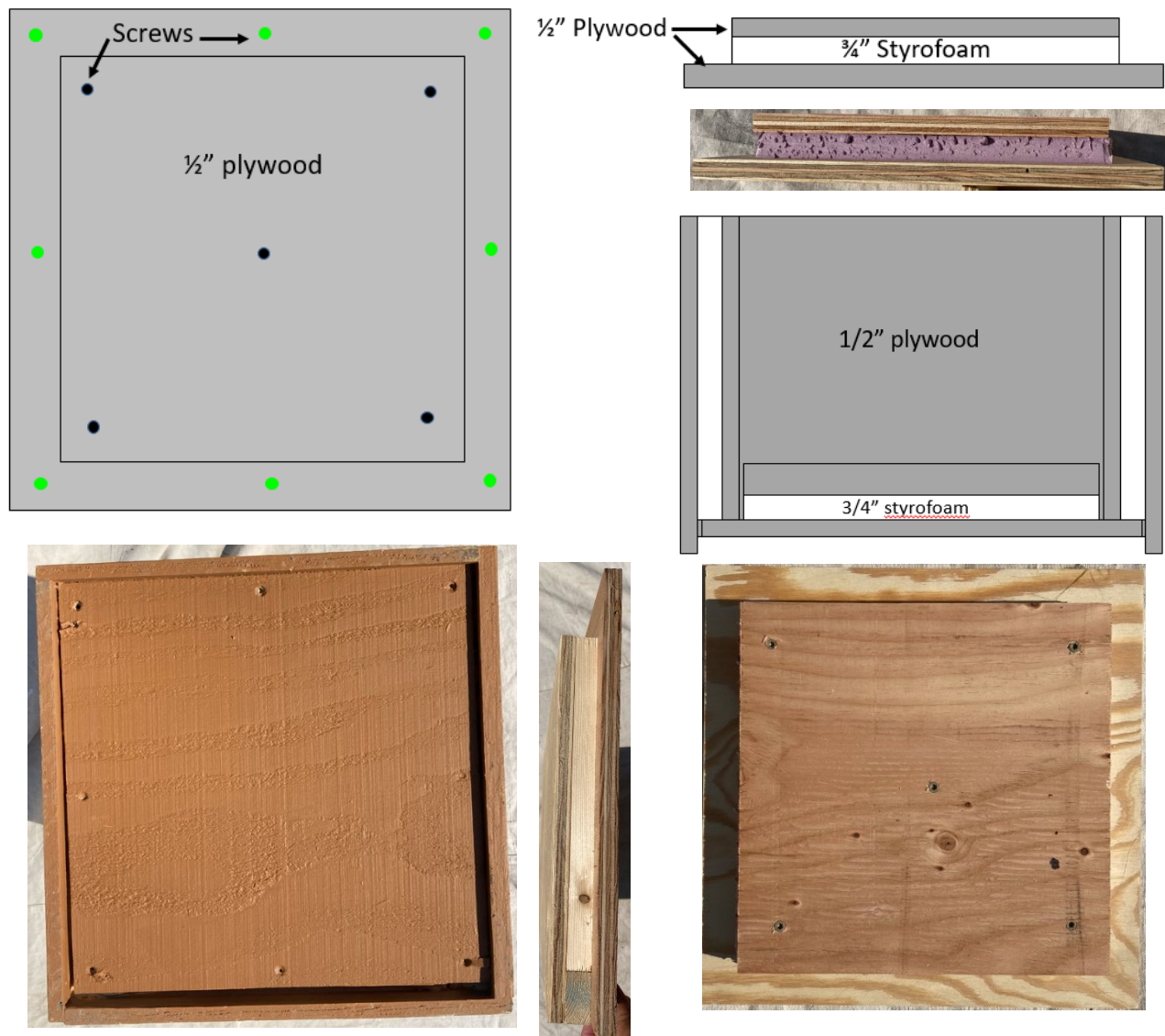
The top panel is relatively simple because there is no extruded polystyrene insulation. Parts 1-A and 1-B are used for the top (Fig. 4). We used 5 screws to attach the 2 plywood pieces together, and 4 screws to attach the top to the sides of the box, with approximate locations as shown in Fig. 4.

Figure 4. Diagram of bottom view of top of den box. The inside piece is slightly offset to create a small lip on the top of the den box, the offset should be as thick as the box ($2 * \frac{1}{2}"$ plywood + $\frac{3}{4}"$ Styrofoam insulation = 2.5").



Parts 4-A, 4-B, and 4-F are used for the bottom of the den box. The extruded polystyrene insulation is sandwiched in between the plywood using 1 5/8" screws from both sides of the bottom plywood pieces. Screws should be spaced about 6" apart and at least 1" from the edge of the plywood. About 13 1 5/8" screws are needed, 5 to attach the plywood pieces together, and 8 to attach the bottom to the sides of the den box. There is about 1/8" of space between Part 4-A and Part 2-A, and also between parts 4-B and 4-F and part 2-B. One modification we made is that pieces 2-B and 2-F were resized so that the bottom would be recessed 1/2" as recommended by Steve Mortenson (Leech Lake Band of Ojibwe). This modification helped reduce bottoms from rotting out of wood duck boxes. The bottom right diagram in Fig. 5 shows how the bottom was recessed, and the bottom left pictures show how the bottom was attached to the sides of the den box.

Figure 5. Top view and side view of bottom of den box. Diagrams are not to the same scale.



Installation of Den Boxes on Trees

Once we were in a forest stand we would search for a tree with a strong enough branch to hold the den box, alternatively we could use trees without branches because there were two cables attaching the den box to the tree (Fig. 6). We generally deployed den boxes from 5 to 12 feet above ground level.

Figure 6. Examples of some deployments of fisher den boxes. For research purposes, we wrote the name of the den box by the opening.



We attached den boxes to trees using galvanized vinyl-coated wire rope (7x7, 3/16" cable). First, we would attach 2x2s to the back of the den box (Fig. 7). We drilled two holes in each 2x2 and fed the wire rope through the holes. Next, we would loop a rope around the branch, attach the rope to the den box, and lift the den box up to the height where it was to be attached to the tree. Alternatively, we would push the den box up from the bottom, reaching as high as possible. Once the lifting rope was tied off on an adjacent tree or being held securely, we would use a ratcheting tie-down to secure the den box to the tree. Next, we would loop the vinyl covered wire cable around the tree and use a wire rope clip (inset on Fig. 7) to hold the wire rope in place.

Figure 7. Steps in attaching a den box to a tree. First, 2x2s are placed on the back of den box to fit the tree bole. The den box is lifted up and a ratchet strap is tightened, after which the wire rope is attached.



After removing the ratcheting tie-down, we would screw a branch onto the den box just below the opening, as is seen in several of the examples in Fig. 6 and Fig. 7. Fishers and other animals would use this branch to enter and exit the den box.

Acknowledgements

Funding for this project was provided by the Environment and Natural Resources Trust Fund for the project “Artificial Den Boxes for Fishers,” M.L. 2019, First Special Session, Chp. 4, Art. 2, Sec. 2, Subd. 03i.

Literature Cited

Davis, L.R. 2016. Fisher (*Pekania pennanti*) artificial reproductive den box study. 16.W.BRG.04 / CAT-16-3-345. Davis Environmental Ltd., 108 Mile Ranch, British Columbia, Canada.

Velander, T.B. 2022. Mechanisms underlying American marten (*Martes americana*) winter rest site selection across the Western Great Lakes Region. M.S. Thesis, University of Minnesota Duluth.



Fisher Den Box

Natural Resources Research Institute

UNIVERSITY OF MINNESOTA DULUTH
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Purpose: Fishers need large tree cavities for raising their young and for use as resting sites. A lack of larger diameter trees with suitable nesting/resting cavities on the landscape may be contributing to the recent decline in the population—loss of nearly half since 2002, according to the Minnesota DNR. It may take time for fishers to find the box, but even if a fisher doesn't, it will likely benefit something! Martens, Squirrels, Grey fox, Owls, and a variety of rodents may also make use.

*This effort is part of an ongoing study by the **Natural Resources Research Institute** (University of Minnesota) and results are preliminary. More information on the effectiveness of the nest boxes in Minnesota will be collected as the study progresses. The project is funded by the Environmental and Natural Resources Trust Fund as recommended by the Legislative-Citizen Commission on Minnesota's Resources.*

Habitat: Fishers live in a variety of young and old forest types in northern Minnesota. Sometimes they are found in southeastern river valleys. They are solitary, except during the breeding season and when the young are with the female. Fishers range over 7 to 10 square miles, traveling at any time of day or night. They are adaptable, but avoid open areas. They prefer the edges of conifer stands when these are adjacent to stands of deciduous trees. Large coarse woody debris (downed trees), hollow standing trees, rock crevices, slash piles, abandoned beaver lodges in dry ponds, and old porcupine dens are preferred resting and foraging sites. For reproduction, female fishers almost exclusively use tree cavities.

Fisher Den Box Dimensions: Two pieces of $\frac{3}{4}$ inch plywood form the walls with 19mm rigid insulating foam in between (See figure 1). The outside dimensions are roughly 16" wide x 35" tall on each side, while the inside dimensions are 12" on each side. The entrance hole is located near the top corner of the box and is about 3" wide x 4" tall (they don't need much—and the smaller opening may help protect from intruders).

Hanging the box: Light chain can be used or plastic-coated cable (3/32", 7x7 cable) to hang boxes on the tree.

Bedding inside the box: Naturally occurring dry or untreated wood chips/mulch piled about 6-8" thick (adds insulation)



(Figure 1)



(Figure 2)

Field Setup:

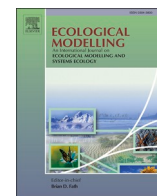
1. Choose a robust tree (> 8" DBH), hoist box so that the bottom is 6 feet off of the ground (fishers are excellent climbers and the height adds safety from predators such as a bobcat).
2. Bring chain around tree and attach over the bolt sticking out the front of the box and/or deck screws/lag screws to connect the box to the tree; gravity holds box in place. Alternatively use plastic-coated cable and fasteners to hang from tree (**see figure 2**).
3. Take a sturdy branch and screw (deck screws with square bits) it into the box and into the tree. The branch adds stability to the box and allows for a perch of sorts (**see figure 3**).



(Figure 3)



(A fisher exits the nest box)



A dynamic thermal model for predicting internal temperature of tree cavities and nest boxes

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Thermoregulation
Microclimate
Heat transfer
American marten
Fisher

1. Introduction

Many mammal and bird species use tree cavities for resting and raising offspring (Moore, 1945; McComb and Noble, 1981b; Isaac et al., 2008; Cockle et al., 2011; Maziarz et al., 2017; van der Hoek et al., 2017). Tree cavities protect inhabitants from predators and harsh weather and provide favorable microclimates. Energetic costs of thermoregulation during periods of extreme ambient temperatures are reduced when birds and mammals use tree cavities (Kendeigh, 1961; Du Plessis et al., 1994; Zalewski, 1997; Sedgeley, 2001; Joyce, 2013; Matthews et al., 2019). Further, favorable thermal conditions in tree cavities may reduce the energetic costs of reproduction, enhance egg viability, and increase offspring growth rate (Wiebe and Swift, 2001; Ardia et al., 2006; Clement and Castleberry, 2013).

Temperatures within tree cavities and other microhabitats are influenced by local weather conditions, site characteristics, and the thermal and structural properties of the microhabitat that modulate heat and mass transfer processes between the microhabitat and its environment (Kearney and Porter, 2017). For example, the tree canopy can partially block solar insolation and decrease local ambient temperatures

in a forest (Leuzinger et al., 2010; Berry et al., 2013; De Frenne et al., 2019). Other site characteristics such as the slope and orientation of the terrain at the tree cavity site also affect site temperature (Suggitt et al., 2011; Méndez-Toribio et al., 2016). Characteristics of the cavity, such as orientation of entrance holes, size of entrance holes, chamber volume, chamber diameter, wall thickness, internal surface area, and the specific heat capacity of the wood surrounding the cavity affect internal cavity temperatures (MacLean, 1941; Sedgeley, 2001; Ardia et al., 2006; Pacfík and Weidinger, 2007; Clement and Castleberry, 2013; Radmanović et al., 2014). For example, temperatures within cavities are more stable and fluctuate less with increasing tree diameter (Coombs et al., 2010). This is partly because increased wood around cavity chambers resists heat flow between the cavity chamber and the external environment. Similarly, temperatures in cavities with many entrance holes or cavities with large entrance holes are likely less stable due to greater air movement into and out of the cavity.

Moisture also plays an important role in microhabitat temperatures when water freezes and thaws. In trees without cavities, for example, internal wood temperature is partially governed by phase changes of water or sap that occur when temperatures reach freeze-thaw (Derby

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and Gates, 1966; Graf et al., 2015; Charrier et al., 2017; Reid et al., 2020; Zhao et al., 2021), which is the temperature range at which water changes between liquid and solid phases. Freeze-thaw for pure water is 0°C, but freeze-thaw can be slightly warmer or cooler for aqueous solutions such as tree sap (Derby and Gates, 1966; Graf et al., 2015; Reid et al., 2020; Zhao et al., 2021). Graf et al. (2015) describe the fundamental phase change dynamics within trees. Water frozen in a tree undergoes a phase change from a solid state to a liquid state as temperatures in the tree reach freeze-thaw. During this phase change, the latent heat of fusion of ice keeps the wood at temperatures around freeze-thaw even if ambient temperature is above freeze-thaw temperatures. This period of relatively constant temperature around freeze-thaw is called a thermal arrest period, and it does not end until the ice fully thaws. Similarly, during freezing, the latent heat of solidification of liquid water creates a thermal arrest period around freeze-thaw until the water has fully solidified. Latent heat of water is also responsible for thermal arrest periods that occur during the freezing and thawing of moist soil (Kudriavtsev et al., 2016; Zhou et al., 2018; Zhang et al., 2020). Phase change of water is also a key component in the development of the subnivium and is a process that allows the subnivium to maintain a temperature of around 0°C throughout the winter in areas with relatively deep snowpack (Cohen, 1994; Thompson et al., 2018; Kearney, 2020). The effects of thermal arrest periods on tree cavity temperatures has not been documented. However, we expect that thermal arrest periods may occur in cavities due to the prevalence of this phenomenon in solid tree stems and other microhabitats.

Many animals select cavities based on the relative thermal benefit they provide. For example, female fishers (*Pekania pennanti*) (Aubry et al., 2013; Matthews et al., 2019), tree swallows (*Tachycineta bicolor*) (Ardia et al., 2006), and bats (Lausen and Barclay, 2003; Ruczyński, 2006) all change cavity selection to match varying cavity temperatures with their changing biological needs. Having the ability to predict the temperature in tree cavities could improve our mechanistic understanding of the role of cavity characteristics on animal selection and ecology, and provide a biological basis for management decisions. Temperature loggers are often used to make a direct connection between animal response and microhabitat temperature (Vonhof and Barclay, 1997; Wiebe, 2001; Paclík and Weidinger, 2007; Isaac et al., 2008; Coombs et al., 2010; Mersten-Katz et al., 2012; Maziarz et al., 2017; Fawcett et al., 2019). Although accurate, temperature loggers are limited to measuring temperatures of a single cavity, cannot predict historical temperatures, and are limited to measuring temperatures until either the memory is filled or the batteries run low. Consequently, the limitations of temperature loggers increase the cost and effort needed to measure tree cavity temperatures, making it relatively difficult for researchers to effectively sample tree cavity temperatures.

An alternative method is to create a model that can be used to predict historical and future temperatures in cavities as a function of changes in weather conditions, habitat characteristics, and cavity characteristics. A variety of thermal modeling approaches have been used to measure or estimate heat flow and temperatures of systems similar to tree cavities. Complex theoretical heat transfer equations can be used to model a broad range of heat and mass transfer processes (Potter and Andresen, 2002; Westermann et al., 2013; Kearney and Porter, 2017; Reid et al., 2020). This modeling approach, however, often requires many parameters and is computationally intensive. An alternative approach is to use theoretical equations that represent the most important processes of heat and mass transfer (Bolstad et al., 1997). Although this approach is simple, it can be less accurate, resulting in a trade-off between model complexity and model accuracy (Gilad-Bachrach et al., 2003). There are also hybrid modeling approaches, which use a simple theoretical structure as the foundation of the model and obtain empirical estimates of the systems temperature to calibrate or fit the model (Bryant and Shreeve, 2002; Maclean et al., 2017; Singh and Tiwari, 2017; Hietaharju et al., 2018; Cui et al., 2019). The hybrid approach can produce accurate results for systems that are measured, but the hybrid model cannot be

extended to other systems without acquiring new empirical temperature measurements for calibration.

There are few studies that predict tree cavity temperatures. Studies that do, however, use data driven approaches that include empirical measurements of tree cavity temperatures as a parameter within the model (Howe et al., 1987; Clement and Castleberry, 2013; Amat-Valero et al., 2014; Güebler et al., 2014). These models cannot be extended to other cavities or different time periods, limiting the scope of their application. They also did not directly predict tree cavity temperatures by accounting for the site-specific abiotic conditions and cavity characteristics that drive the heat and mass transfer of energy between the cavity and external environment. For example, Amat-Valero et al. (2014) used measured cavity temperatures and relative humidity to calculate the apparent, or perceived, temperature in tree cavities. Although the model they developed was useful, it required them to measure tree cavity temperature, which further supports the need for an alternative way to obtain cavity temperature.

In this study we describe a theoretical thermal model that accurately predicts temperature in tree cavities over time. The model requires a relatively small set of measurements for parameterization but has a tractable complexity that captures the main heat and mass transfer processes that drive temperature within the tree cavity. It is also generalizable, allowing researchers to use the model on different tree cavities that experience different ambient temperatures, and vary in physical, thermal, and site characteristics. The model uses ambient temperature and cavity-specific thermal and physical characteristics to predict the temperatures within tree cavities over time. Our objectives were to: 1) define a tree cavity system by identifying the major processes of heat and mass transfer that influence cavity temperatures; 2) describe a thermal model that incorporates the major heat and mass transfer processes to estimate cavity temperatures; and 3) test the model's ability to accurately predict temperatures in tree cavities. We also tested the model's ability to predict temperatures in den boxes, which are known to be important alternative microhabitats in areas where natural tree cavities are limited (McComb and Noble, 1981a; Mänd et al., 2005; Lindenmayer et al., 2009; Goldingay et al., 2015; Maziarz et al., 2017).

2. Methods

2.1. Defining the cavity system

Temperature within a cavity chamber varies over time as energy is constantly exchanged between the environment and the cavity. Thermal equilibrium is unlikely to be reached because of daily cycles in ambient temperature. Energy flow equations can account for a cavity's transient flow of energy by using partial derivatives (Potter and Andresen, 2002; Reid et al., 2020). An alternative approach is to treat cavity systems as a lumped capacitance reservoir of heat, which simplifies transient heat analyses by removing the space variable and allowing temperature to be predicted as a function of time, and assume radiation and convection are negligible (Hudson and Underwood, 1982; Kossak and Stadler, 2015; Hietaharju et al., 2018). Using these simplifying assumptions, we treated a tree cavity system as a lumped capacitance reservoir of heat with two main processes of heat and mass transfer occurring (Fig. 1): (1) conductive heat (Q_{cond}) transferred between ambient air and the cavity system; and (2) the displacement of air and the associated heat (Q_{hole}) through one or more entrance holes.

2.2. Cavity model description

The model we describe uses a framework of heat and mass transfer equations similar to the equations described by Kossak and Stadler (2015) and Hietaharju et al. (2018). We modified the use of these equations for tree cavities and den boxes that would be used by animals.

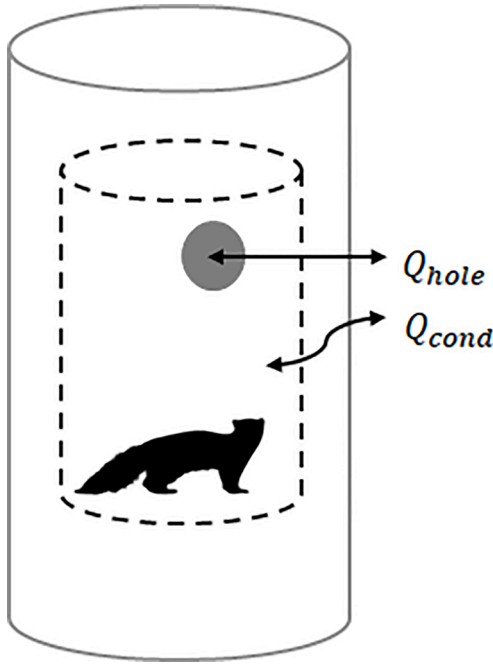


Fig. 1. Schematic of the primary heat and mass transfer processes in a tree cavity system. Q_{cond} is the conductive heat transferred between ambient air and the cavity system, and Q_{hole} is the mass transfer of air through an entrance hole (s). Both Q_{cond} and Q_{hole} are expressed in joules (J). The dashed line represents the cavity chamber.

2.2.1. Energy change equations

The energy transfer rate (Watts) through any system is equal to the sum of the energy transfer rates in and out of the system. Eq. (1) describes the energy transfer rate through a cavity system based on Q_{cond} and Q_{hole} :

$$\frac{dQ_{cavity}}{dt} = \frac{dQ_{cond}}{dt} + \frac{dQ_{hole}}{dt} \quad (1)$$

where $\frac{dQ_{cavity}}{dt}$ is the cumulative energy transfer rate through the cavity system, $\frac{dQ_{cond}}{dt}$ is the conductive heat transfer rate between the ambient air and the cavity system, and $\frac{dQ_{hole}}{dt}$ is the mass transfer rate of air moving through the entrance hole(s) of the cavity system.

Heat transfer between the ambient air and the inside cavity chamber is resisted by all sides of the cavity chamber except the entrance hole(s). A side is comprised of one or more layers of material (i.e., wood, bark, insulation). The conductive heat transfer through a single side of a cavity can be expressed as the product of the overall heat transfer coefficient of the side, the outer surface area of the side, and the difference between the ambient temperature and the temperature of air in the cavity:

$$\frac{dQ_{cond}}{dt} = U_s A_s [T_a - T_{in}] \quad (2)$$

where U_s is the overall heat transfer coefficient of a side (W/m^2K) and is calculated using the thermal conductivity (W/mK) and thickness (m) of each layer of the side (Bergman et al., 2011), A_s is the outer surface area of the side (m^2), T_{in} is the internal cavity temperature (K), and T_a is the ambient air temperature outside the cavity (K). To account for conductive heat transfer through all sides of a cavity chamber, the heat loss coefficient $U_s A_s$ (W/K) can be calculated as the sum of the products of the overall heat transfer coefficients and surface areas of each side of the cavity (Kossak and Stadler, 2015):

$$U_s A_s = \sum_{i=1}^n U_{s(i)} A_{s(i)} \quad (3)$$

where $U_{s(i)}$ is the overall heat transfer coefficient of side i (W/m^2K), and $A_{s(i)}$ is the outer surface area of side i (m^2).

The mass transfer rate of air moving through the entrance hole(s) of a cavity system is calculated from volumetric air flow into the cavity through the entrance hole(s), the density of the ambient air, the isobaric specific heat capacity of the ambient air, and the temperature difference between the internal air volume and the ambient air (Kossak and Stadler, 2015):

$$\frac{dQ_{hole}}{dt} = (\dot{V}_{air} \times \rho_{air_a} \times C_{p,air_a}) [T_a - T_{in}] \quad (4)$$

where $\dot{V}_{air}$ is the volumetric air flow into the cavity through entrance hole(s) (m^3/s), and is estimated as the product of the surface area (m^2) of the entrance hole and the speed (m/s) at which air is moving through. ρ_{air_a} is the density of the ambient air (kg/m^3), and C_{p,air_a} is the isobaric specific heat capacity of the ambient air (J/kgK).

In a cavity system, heat and mass transfer processes act on two separate heat sinks (Kossak and Stadler, 2015): the air volume in the cavity chamber, and the materials such as wood, bark, bedding material, or insulation that make up the cavity structure (Fig. 1). We accounted for heat and mass transfer through each of these sinks by re-expressing Eq. (1) as the sum of the energy transfer rate through the air volume and the energy transfer rate through the material volume:

$$\frac{dQ_{air}}{dt} + \frac{dQ_m}{dt} = \frac{dQ_{cond}}{dt} + \frac{dQ_{hole}}{dt} \quad (5)$$

where $\frac{dQ_{air}}{dt}$ is the energy transfer rate through the air volume in the system and $\frac{dQ_m}{dt}$ is the energy transfer rate through the material volume.

2.2.2. Modified energy change equations

Eqs. (1–5) predict energy change of the cavity system over time. We can predict temperature change over time using the heat capacity (J/K) of the air and the heat capacity of the materials (Kossak and Stadler, 2015; Hietaharju et al., 2018). We expressed the energy change (J) of the air volume in the system as the product of the heat capacity of the air and the change in air temperature in the cavity chamber, with heat capacity of air being equivalent to the product of the volume, density, and isobaric specific heat capacity of the air mass:

$$dQ_{air} = C_{air} \times dT_{in} = (\dot{V}_{air} \times \rho_{air_{in}} \times C_{p,air_{in}}) \times dT_{in} \quad (6)$$

where C_{air} is the heat capacity of the air volume in the cavity chamber (J/K), dT_{in} is the change in air temperature in the cavity chamber (K), $\dot{V}_{air}$ is the volume of the air in the cavity chamber (m^3), $\rho_{air_{in}}$ is the density of air in the cavity chamber (kg/m^3), and $C_{p,air_{in}}$ is the isobaric specific heat capacity of air in the cavity chamber (J/kgK).

The energy change through a material volume is the product of the heat capacity of the material volume and the change in air temperature inside the cavity:

$$dQ_m = C_m \times dT_{in} \quad (7)$$

where C_m is the heat capacity of the material volume (J/K). The cavity system, however, can be composed of several materials, with each material having its own heat capacity value. Because we are treating the cavity as a lumped capacitance system, the heat capacity of the material volume (C_m) is calculated as the sum of the heat capacities of all materials in the cavity system, with the heat capacity of material i equal to the product of its specific heat capacity, its volume, and its density:

$$C_m = \sum_{i=1}^n C_{m(i)} = \sum_{i=1}^n C_i \times V_i \times \rho_i \quad (8)$$

where $C_{m(i)}$ is the heat capacity of material i (J/K), C_i is the specific heat capacity of material i (J/kgK), V_i is the volume of material i (m^3), and ρ_i

is the density of material i (kg/m^3). Eq. (5) can now be re-evaluated as:

$$\left(C_m \times \frac{dT_{in}}{dt}\right) + \left(C_{air} \times \frac{dT_{in}}{dt}\right) = \frac{dQ_{cond}}{dt} + \frac{dQ_{hole}}{dt} \quad (9)$$

Eq. (9) can be expressed as a first order differential equation, where air temperature in the cavity chamber at time t can be predicted using values of T_{in} and T_a at the previous time step ($t - 1$):

$$T_{in(t)} = T_{in(t-1)} + \frac{\Delta t}{(C_m + C_{air(t-1)})} \left[(U_s A_s [T_a(t-1) - T_{in(t-1)}]) + ((\dot{V}_{air} \times \rho_{air_a(t-1)} \times C_{p,air_a(t-1)}) [T_a(t-1) - T_{in(t-1)}]) \right] \quad (10)$$

$T_{in(t)}$ is the predicted internal temperature (K) at the current time step (t), $T_{in(t-1)}$ is the estimated internal temperature at the previous time step ($t - 1$), $T_a(t-1)$ is the ambient temperature (K) at the previous time step ($t - 1$), and Δt is the time interval (seconds) between t and $t - 1$. Because the density and isobaric specific heat capacity of air changes with temperature, $C_{air(t-1)}$ is the heat capacity of the air volume in the cavity chamber at ($t - 1$), $\rho_{air_a(t-1)}$ is the density of ambient air (kg/m^3) at ($t - 1$), and $C_{p,air_a(t-1)}$ is the isobaric specific heat capacity of ambient air (J/kgK) at ($t - 1$).

2.3. Model evaluation

2.3.1. Study areas

The Superior and Chippewa National Forests, Minnesota USA, are described by Joyce (2013), and Berg et al. (2020). Superior National Forest is in northeastern Minnesota (47.30 °N, 91.52 °W), and consists of four main forest cover types: mixed coniferous-deciduous forest, lowland conifer, upland conifer, and deciduous forest. The Chippewa National Forest is in north-central Minnesota, near Remer, Minnesota (47.06 °N, 93.91 °W), and consists mostly of deciduous forest, with areas of open water, wetlands, regenerating and mixed forests.

The Huron-Manistee National Forest, Michigan USA, was described by Sanders et al. (2017). The study area is in Michigan's northern lower peninsula (44.42 °N, 85.40 °W), and consists of a variety of upland forest types such as mixed-hardwood and second-growth conifer stands.

2.3.2. Field data collection

We collected ambient and cavity temperature data at 22 cavities in the Chippewa and Superior National and 21 cavities in the Huron-Manistee National Forest. The cavities we measured were used by American martens (*Martes americana*) and fishers during previous radiotelemetry studies. We selected a sub-sample from 218 cavities previously identified in Minnesota and 143 cavities previously identified in Michigan (Joyce, 2013; Erb et al., 2015; Sanders et al., 2017). We used a stratified random sampling design to select cavities to sample based on three strata for tree diameter and three strata for cavity hole height above ground. We constrained the final sample to be similar to tree species composition, tree diameter, and status (live or dead) of trees used by martens or fishers. Our final sample included cavities in quaking aspen trees ($N = 12$, *Populus tremuloides*), northern white cedar trees ($N = 6$, *Thuja occidentalis*), red maple trees ($N = 3$, *Acer rubrum*), and a paper birch tree ($N = 1$, *Betula papyrifera*) in Minnesota. We sampled cavities in oak trees ($N = 15$, *Quercus* spp.), bigtooth aspen trees ($N = 2$; *Populus grandidentata*), and sugar maple trees ($N = 4$, *Acer saccharum*) in Michigan. We sampled 29 cavities in live trees and 14 cavities in dead trees. Trees in Minnesota had an average diameter at breast height (DBH) of 43.2 cm (SD = 10.9, range = 26.7–71.9), while trees in Michigan had an average DBH of 57.8 cm (SD = 18.7, range =

36.1–96.5). Average cavity height above the ground in Minnesota was 3.2 m (SD = 1.8, range = 0.6–8.3), while average cavity height above ground in Michigan was 3.3 m (SD = 2.3, range = 0–8.4).

We also tested the model on 27 fisher den boxes (hereafter, artificial cavities) installed in the Chippewa and Superior National Forests. Artificial cavities were made from plywood or a combination of plywood and foam insulation and were used in a fisher habitat improvement

study in northern Minnesota (M. Joyce, unpublished data). Artificial cavities were installed 2.5–3 m above ground on live trees.

For natural cavities, we measured each cavity using the entrance hole(s) as the access point. We used a string with washers tied to the end to measure distance to the floor of the cavity, a length of 16-gauge wire to measure the distance to the ceiling of the cavity, a diameter tape to measure the diameter of the bole at cavity entrance height, and a tape measure to measure inside diameter, the thickness of the wood surrounding the inner cavity, and entrance hole height and width. The thickness of the wood surrounding the inner cavity was estimated by taking the difference between the total diameter of the tree cavity and cavity chamber diameter and dividing by two. We used the tree cavity measurements to calculate the volume of the internal cavity space, the volume of wood and bark, the total surface area of the cavity, and the area of the entrance hole. We calculated these values by assuming the entrance hole is the shape of an ellipse, the entire cavity system was a cylinder, the internal cavity space was a cylinder, and that the thickness of wood around the cavity was uniform (Clement and Castleberry, 2013). Conductive heat transfer from the ambient air to the inner cavity space occurs through the ceiling of the cavity chamber, the floor of the cavity chamber, and the wall surrounding the cavity chamber. For calculation purposes we assumed all sides of the cavity had the same thickness and thermal properties. We assumed the bark layer had the same thermal properties as the wood layer. Wood density, specific heat capacity, and thermal conductivity of the cavity wood (Table 1) were estimated from literature values for each tree species (Dunlap, 1912; TenWolde et al., 1988; Hedlund and Johansson, 2000; Repola, 2006). Each cavity varied in its physical and thermal characteristics (Supplementary S1 and S2).

Table 1

Density, specific heat, and thermal conductivity values used for estimating model parameters.

Material	Density (kg/m^3)	Specific Heat Capacity (J/kgK)	Thermal Conductivity (W/mK)
Maple wood (<i>Acer</i> spp.)	660	1369	0.18
Aspen wood (<i>Populus</i> spp.)	410	1377	0.12
Oak wood (<i>Quercus</i> spp.)	720	1361	0.19
Cedar wood (<i>Thuja</i> spp.)	385	1357	0.09
Pine plywood (<i>Pinus</i> spp.)	580	1369	0.10
Aspen plywood (<i>Populus</i> spp.)	580	1369	0.10
Douglas fir plywood (<i>Pseudotsuga menziesii</i>)	525	1360	0.12
Extruded polystyrene	33	1428	0.03
Woodchip bedding	196	1200	–
Pine boards (<i>Pinus</i> spp.)	500	1200	–

There were five different artificial cavity designs tested. Dimensions, design, and construction materials used were similar to those used for a previous fisher den box study (Davis and Horley, 2015). The materials of each artificial cavity included the construction materials of the cavity and 13 cm of wood chip bedding material placed at the bottom of the internal cavity space. Construction materials included pine, aspen, or Douglas fir plywood and extruded polystyrene insulation (Owens Corning, Foamular 250, 1.9 cm, R-4). Four of the artificial cavity types had sides that were constructed of two layers of untreated plywood with polystyrene insulation between them. The fifth artificial cavity type had a single layer of treated plywood, 3.8 cm x 3.8 cm pine boards for an internal frame, and no insulation. Each artificial cavity had a 7.6 cm x 10.2 cm rectangular entrance hole. For each artificial cavity we measured internal cavity volume, total volume of materials, and thickness of each construction material. We used these measurements to calculate the internal air volume, the volume of the construction materials, and the total surface area of the cavity. Density, specific heat capacity, and thermal resistance values for plywood, pine boards, woodchips, and insulation (Table 1) were estimated from literature values or obtained in the lab (Dunlap, 1912; MacLean, 1941; TenWolde et al., 1988; Kamke, 1989; Ragland et al., 1991; Osanyintola et al., 2005; Al-Ajlan, 2006; Asdrubali et al., 2015). Like natural cavities, each artificial cavity type varied in its physical and thermal characteristics (Supplementary S3). The 1.3 cm (1/2 inch) aspen plywood, and 1.6 cm (5/8 inch) Douglas fir plywood cavities were stained to prevent rotting and moisture build-up.

Ambient and internal temperatures were measured at 30 minute intervals for each cavity using temperature loggers (HOBO® UA-001-64 pendant data loggers for 4 natural cavities; or MX2201 for all den boxes and the remaining natural cavities, Onset Computer Corporation, Massachusetts, USA). For both cavity types, ambient temperature loggers were hung at chest height or next to the cavity hole and were housed in two white funnels to prevent the effects of wind and solar radiation. For natural cavities, internal loggers were either hung ~ 5 cm above the bottom of the cavity with fishing line or placed on the bottom of the cavity if the logger could not be hung. Internal loggers were positioned ~ 5 cm above the bedding material in artificial cavities. All loggers were set to measure temperature in degrees Celsius. For modeling, ambient temperatures were converted to Kelvin scale. Modelled temperatures were then converted back to degrees Celsius for data presentation.

We assumed air was moving at a constant velocity through the entrance hole was 0.1 m/s, which is similar to the standard air velocity in houses (Standard, 2005; American Society of Heating, Refrigerating and Air Conditioning Engineers, 2010). This assumption is higher than the air speed found in Wachob's (1996) study on Mountain Chickadee nest boxes (< 0.05 m/s). However, the 25 mm diameter of the entrance hole of the nest boxes in their study was significantly smaller than entrance holes to tree cavities or artificial den boxes we used, which likely restricted air flow between their nests and the outer environment.

The density of air at 1 atmospheric pressure decreases from 1.45 kg/m³ at -30°C to 1.16 kg/m³ at 30°C. Isobaric specific heat capacity of air varies from 1003 J/kg*K at -30°C to 1005 J/kg*K at 30°C. For our study, we used a constant air density value of 1.29 kg/m³ (at 0°C) and constant isobaric specific heat capacity value of 1004 J/kg*K (at 0°C) to fit the model. Using constant values of density and specific heat capacity of air simplifies model computation and has a small effect on model results because the overall heat capacity of air is several orders of magnitude less than the overall heat capacity of the materials.

Based on the cavity-specific physical and thermal parameters and site-specific ambient temperature measurements described above, we modeled the internal temperature of each cavity throughout its measurement period using Eq. (10) (see R script in supplementary materials). We used the first internal temperature measurement as the initial temperature value used for variable $T_{in(t-1)}$. Predicted temperature at time t ($T_{in(t)}$) was then calculated at 30 minute intervals ($\Delta t = 1800$ s)

throughout the rest of the monitoring period using modeled internal temperature and measured ambient temperature at time $t - 1$.

2.4. Data analysis

2.4.1. Assessing model accuracy

We evaluated model accuracy using root mean squared error (RMSE). For each cavity, we calculated model error at each sampling interval as the difference between measured and modeled cavity temperature. Model error was used to calculate daily RMSE for each cavity and an overall RMSE for the entire deployment.

We used three generalized estimating equation models (GEE, $\alpha = 0.05$) to evaluate sources of error in the model. GEEs allowed us to test the generalizability of the model while accounting for the temporal correlation between measurements (Zeger and Liang, 1986). GEE model 1 assessed differences in daily RMSE as a function of cavity type (*cavityType*: Natural or Artificial cavity). GEE model 2 assessed differences in daily RMSE within artificial cavities as a function of artificial cavity types (*ArtificialType*: Artificial cavity types). GEE model 3 assessed differences in daily RMSE within natural cavities as a function of study area (*studyArea*), the total heat capacity of the materials (*Cm*), the total heat transfer coefficient of the cavity sides (*Uw*), total material volume (*matVol*), outer cavity surface area (*cavSA*), entrance hole area (*holeA*), total cavity diameter (*cavDia*), and average thickness of the wood that makes up the side of the cavity (*sideThickness*). Due to unequal sample sizes, we did not include tree species or tree condition as covariates within GEE model 3. We assessed collinearity between covariates with scatter plot matrices that included locally weighted smoothing and Spearman correlation coefficients. Preliminary analyses identified high collinearity between *subVol* and *cavSA* ($r = 0.87$), *matVol* and *Cs* ($r = 0.93$), and *cavDia* and *sideThickness* ($r = 0.74$). Therefore, we removed *matVol* and *cavDia* covariates from the model.

For all models, we assumed a Gaussian error distribution and an autoregressive correlation structure that allows higher correlation for daily RMSE values taken closer together than those taken further apart. We also used Tukey's Honest Significant Difference (Tukey's HSD, $\alpha = 0.05$) as a post hoc analysis to make pairwise comparisons. We performed all analyses in R (Version 4.1.1) with package 'geepack' (Halekoh et al., 2006). We assessed assumptions of normality and equal variance using diagnostic plots (quantile-quantile plots, plots of residuals vs. predictor variables, and scale location plots). We also used Cook's distance plots to assess leverage from outliers.

2.4.2. Thermal arrest periods

Results showed that natural cavities exhibited temperature patterns similar to thermal arrest periods identified in solid tree stems. For analysis, a thermal arrest interval was identified when the absolute value of ($T_{in(t)} - \text{model error}$) was less than 1°C. Thermal arrest periods occurred when there were ≥ 2 consecutive thermal arrest intervals. A day for which a thermal arrest period was identified was considered a thermal arrest day. We selected a random subset of all thermal arrest periods identified by this method and manually inspected the predicted and modeled cavity temperatures to confirm a thermal arrest period had occurred.

We identified the ambient and modeled temperatures that were associated with the thermal arrest periods. Because the occurrence of thermal arrest periods is likely related to ambient temperature and the temperature in the tree, we assessed whether ambient and modeled temperature could be used as indicators for thermal arrest periods. We used ambient temperatures between -1 and 1°C for the temperature range when freeze-thaw conditions could occur. To test if these periods significantly affected daily RMSE, we added a fixed covariate, *ThermalArrest*, to GEE model 3 to evaluate differences in daily RMSE between thermal arrest days and days that were not thermal arrest days.

2.4.3. Evaluating bias

We evaluated systematic bias in model results by calculating average daily bias for each sampled artificial cavity, and average daily bias for natural cavities across days with and without a thermal arrest period. We also calculated bias for each thermal arrest period identified.

3. Results

3.1. Model accuracy

We monitored natural cavities for 5884 days (Minnesota; 2953, Michigan; 2931) with 282432 temperature measurements. Average sampling period for natural cavities was 137 (SD = 33) days. Average ambient temperatures ranged from -19.6°C (SD = 1.4°C) to 28.0°C (SD = 2.9°C) for natural cavities in Michigan, and from -30.1°C (SD = 15.6°C) to 27.2°C (SD = 8.8°C) for natural cavities in Minnesota. We monitored artificial cavities for 4598 days (220704 temperature measurements), with an average of 166 (SD = 75) days sampled per artificial cavity. Average daily ambient temperature ranged from -32.6°C (SD = 6.1°C) to 29.1°C (SD = 10.7°C) for artificial cavities. Average absolute difference between ambient and cavity temperature varied between structures from 0.41 to 3.95°C for natural cavities, and 0.99 – 3.56°C for artificial cavities (Supplementary Tables S7, S8 and S9).

Natural cavities had an average RMSE of 1.77°C (SD = 0.66°C , range = 0.42 – 3.65°C) across the full monitoring periods from both states. Artificial cavities had an average RMSE of 1.02°C (SD = 0.45°C , range = 0.42 – 1.94°C). The model-predicted internal cavity temperatures were consistent with measured internal cavity temperature and followed daily oscillations in ambient temperature throughout each monitoring period (Fig. 2A–D). Supplementary material S4, S5, and S6 summarize RMSE for each natural and artificial cavity sampled.

Average daily RMSE across all cavities (natural and artificial) monitored was 1.20°C (SD = 1.03°C). Daily RMSE was lower for artificial cavities (0.83°C , SD = 0.63°C , range = 0.04 – 4.7°C) than for natural cavities (1.47°C , SD = 1.20°C , range = 0.05 – 12.56°C ; GEE, Wald = 40.5, $P < 0.001$).

For artificial cavities, there were significant main effects of box design (GEE, $F_{4, 4593} = 7.5$, $P < 0.001$). Daily RMSE was slightly higher in the uninsulated 1.9 cm (3/4 inch) pine plywood cavity compared to the insulated 1.9 cm (3/4 inch) pine plywood cavity (Tukey's HSD, $P <$

Table 2

Summary of daily root mean squared error (RMSE) for five artificial cavity types tested.

Cavity Type	Mean	SD	Min	Max
Insulated 1.9 cm Pine plywood	0.62	0.38	0.10	2.09
Insulated 1.3 cm Pine plywood	0.75	0.69	0.05	4.48
Insulated 1.3 cm Aspen plywood	0.92	0.59	0.06	3.02
Insulated 1.6 cm Douglas fir plywood	0.73	0.52	0.04	3.98
Uninsulated 1.9 cm Pine plywood	1.41	0.83	0.12	4.71

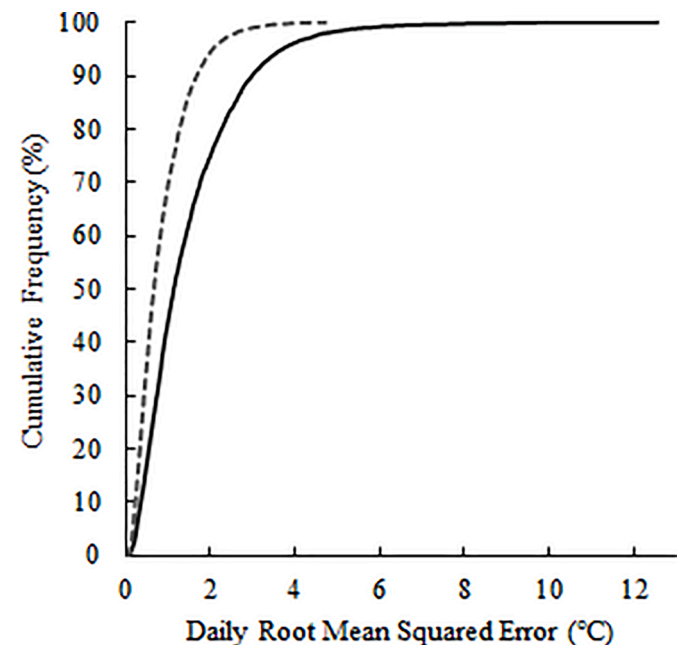


Fig. 3. Cumulative frequency distribution of daily root mean squared error (RMSE) for natural (black line) and artificial cavities (dashed gray line) calculated across all cavities and all monitoring days.

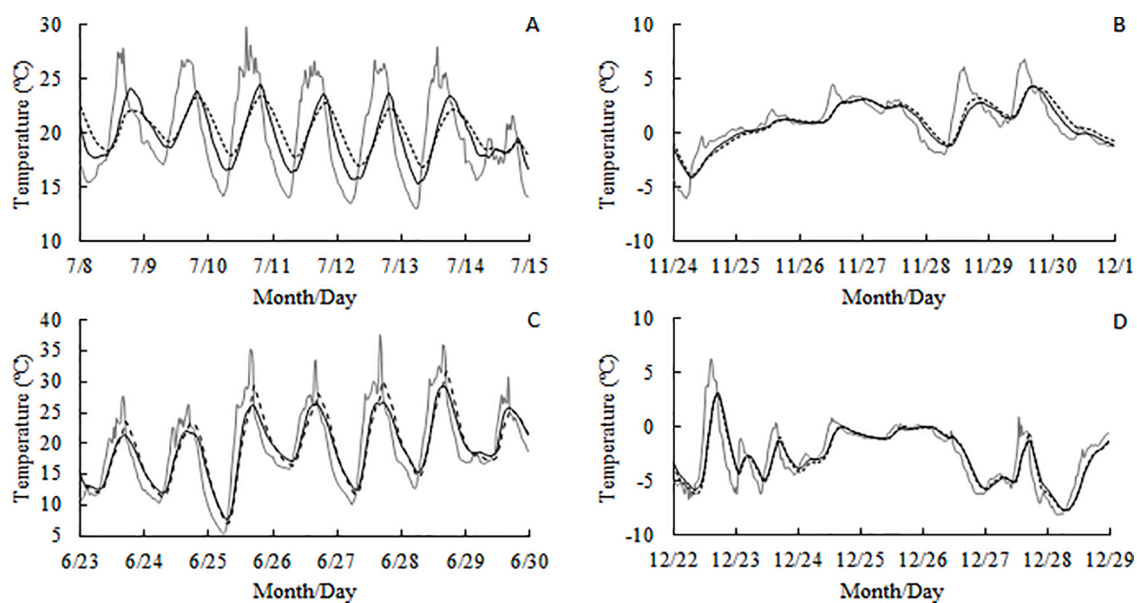


Fig. 2. Results across a sampled week in two natural cavities (A–B) and two artificial cavities (C–D). The solid gray line describes the ambient temperature. Measured temperature in the cavity is expressed with the solid black line. Modeled temperature is expressed as the dashed black line. Fig. A–C occurred in year 2020, Fig. D occurred in 2019.

0.001) and compared to the insulated 1.6 cm (5/8 inch) Douglas fir plywood cavity (Tukey's HSD, $P = 0.01$, Table 2). Daily RMSE was slightly higher in the insulated 1.3 cm (1/2 inch) aspen plywood cavity compared to the insulated 1.9 cm (3/4 inch) pine plywood cavity (Tukey's HSD, $P = 0.02$, Table 2).

For natural cavities, there were no significant main effects for study area (*studyArea*, Wald = 1.26, $P = 0.26$), the total heat capacity of the materials (*Cm*, $\beta < 0.001$, Wald = 0.346, $P = 0.56$), the total heat transfer coefficient of the cavity sides (*Uw*, $\beta = -0.34$, Wald = 1.59, $P = 0.21$), the outer surface area of the cavity (*cavSA*, $\beta = -0.08$, Wald = 0.46, $P = 0.50$), the entrance hole area (*holeA*, $\beta = 27.7$, Wald = 3.41, $P = 0.06$), or the average thickness of the wood on the side of the cavity (*sideThickness*, $\beta = -3.24$, Wald = 0.60, $P = 0.44$).

For natural cavities, 75% of sampled days (4413 days) had less than 2 °C RMSE (Fig. 3) when days with and without thermal arrest periods were included in calculations. Of the 1471 days with RMSE greater than 2 °C, almost half (716 days) were days with a thermal arrest period and about 20% (272 days) occurred within 48 hours after a day that contained the end of a thermal arrest period. The 483 days with RMSE greater than 2 °C that were greater than 48 hours after a thermal arrest period ended occurred across a broad range of average ambient temperatures (mean = -5.23 °C, SD = 16.1 °C, range = -30.2–24.9 °C). Overall, for natural cavities 92% of all sampled days either had RMSE less than 2, contained a thermal arrest period, or occurred within 48 hours of thermal arrest period, while 8% of all sampled days had RMSE greater than 2 outside of a thermal arrest period.

For artificial cavities, 95% of sampled days (4347 days) had less than 2 °C RMSE (Fig. 3). Days with RMSE greater than 2 °C occurred across a broad range of average ambient temperatures (mean = 3.95 °C, SD = 11.9 °C, range = -26.3–24.3 °C). About half (46%) of all days with RMSE greater than 2 °C occurred in the artificial cavity without foam insulation, and 20% of all days with RMSE greater than 2 °C occurred in the 1.3 cm (1/2 inch) aspen plywood artificial cavity.

3.2. Thermal arrest periods

There were 1843 thermal arrest periods over 2343 days identified in natural cavities (Minnesota: 807; Michigan: 1036, Fig. 4). In Minnesota, thermal arrest periods accounted for 11% of the intervals sampled, while in Michigan they accounted for 33% of the intervals sampled. On average thermal arrest periods lasted for 17 hours (median = 6 hours, SD = 43.8 hours, range = 1–1235 hours) with 70% of all thermal arrest periods lasting less than 12 hours, 10% of thermal arrest periods lasting between 12 and 20 hours, and 10% of thermal arrest periods lasting between 20 and 48 hours.

Average thermal arrest period temperature was -0.11 °C (SD = 0.44, range = -0.99–0.98). Thermal arrest periods followed expected phase change dynamics, in that temperature stabilized every time the cavity

reached temperatures between -1 and 1 °C. In many cases, especially during long thermal arrest periods, ambient and modeled temperatures oscillated between positive and negative temperatures during the thermal arrest period (e.g. Fig. 4B). The longest thermal arrest period lasted 1234.5 hours (~51 days), ambient temperature oscillated above and below freeze-thaw temperatures 69 times, and modeled temperature oscillated between freeze-thaw temperatures 13 times. The number of oscillations was positively correlated with the length of the thermal arrest period.

There were significant main effects for days that exhibited thermal arrest (*ThermalArrest*) (GEE, Wald = 9.87, $P = 0.002$). Days without thermal arrest periods had slightly lower RMSE (1.34 °C, SD = 1.02 °C, range = 0.06–8.11 °C) than days with a thermal arrest period (1.68 °C, SD = 1.39 °C, range = 0.05–12.56 °C). Nonetheless, most thermal arrest periods had low error. For example, 69% of days with a thermal arrest period had less than 2 °C RMSE, and 87% of days with a thermal arrest period had less than 3 °C RMSE. In contrast, 79% of days without a thermal arrest period had less than 2 °C RMSE, and 92% had less than 3 °C RMSE.

We found that modeled temperature was a relatively strong indicator of thermal arrest periods. A thermal arrest period occurred on 88% of days when modeled cavity temperatures were between -1 and 1 °C. Ambient temperature was a weaker indicator of when a thermal arrest period would occur. A thermal arrest period occurred on 63% of days when ambient temperatures were between -1 and 1 °C.

3.3. Bias

Average daily bias for artificial cavities was -0.06 °C (SD = 0.30, range = -0.85–0.34). For natural cavities, average daily bias for days that did not have a thermal arrest period was 0.06 °C (SD = 0.51, range = -1.13–1.40). Average daily bias for days with a thermal arrest period was -0.49 °C (SD = 0.48, range = -1.40–0.34). Average bias for thermal arrest periods was -0.56 °C (SD = 1.84, range = -10.1–9.98).

4. Discussion

The temperature in a tree cavity system is governed by complex interactions between energy transfer processes, ambient conditions, habitat characteristics, and physical and biological properties of the cavity. The described model simplifies these complex interactions into two main modes of energy transfer that can be calculated from a relatively small set of input parameters. Despite the simplifying assumptions that the model is based on, it accurately predicted cavity temperature for both natural and artificial cavities for several months across broad ambient temperature ranges. Our sampling period RMSE values were similar to RMSE values for more complex thermal models predicting the temperature within solid tree stems (Potter and Andresen, 2002; Reid

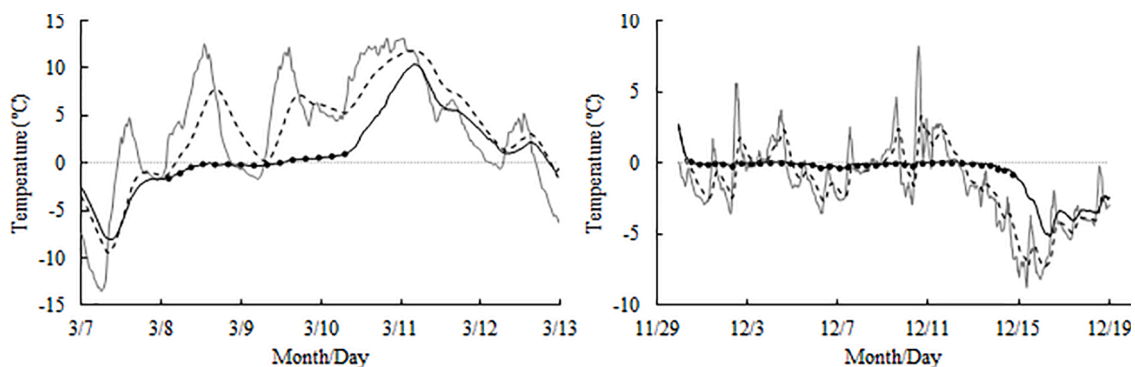


Fig. 4. Multiple day results of natural cavities with thermal arrest periods at 0 °C. The solid gray line describes the ambient temperature. Modeled temperature is expressed as the dashed black line. Measured temperature in the cavity is expressed with the solid black line. The thermal arrest period(s) is expressed as the large dotted black line. The dotted horizontal gray line represents 0°. Figures A occurred in year 2021, while Fig. B occurred in 2020.

et al., 2020). RMSE values were also similar to RMSE values for a complex thermal model used to predict microclimate temperature throughout snow and soil profiles (NicheMapR; Kearney et al. 2014; Kearney and Porter 2017; Fitzpatrick et al. 2019; Kearney 2020). Additionally, GEE analyses showed that our model performed consistently in cavities with different thermal and physical characteristics and across two study areas with different thermal conditions. This suggests that the model can be applied to cavities in different tree species, different cavity sizes, and forest conditions. We also found almost no bias in error for both artificial and natural cavities, indicating that there were no systematic tendencies such as effects of radiation and convection that caused differences between modeled and measured temperatures. This further shows that the energy processes included in the model are likely the most important processes governing cavity temperatures.

We found the model predicted temperatures in artificial cavities better than in natural cavities. Thermal arrest periods accounted for some of the error in natural cavities, but differences are also likely related to increased error when measuring the physical characteristics of natural cavities. Surface area and volume of natural cavities, for example, could not be measured as precisely as surface area and volume of artificial cavities. Because the model predicts temperature as a function of the physical and thermal characteristics of the cavity, any error in estimates of cavity characteristics could contribute to error in the model. Other simplifying assumptions, such as our assumption that each natural cavity was a perfect cylinder, or the ceiling and floor were the same thickness as the outer side, would contribute to model error for natural cavities. Future work could focus on methods that would allow more precise estimates of natural cavity characteristics. For example, accuracy could potentially improve by cutting down the cavities to obtain accurate measurements of the physical properties of cavities. However, given the concerns over availability of large trees with cavities (e.g., Lindenmayer et al. 2012), and that error was relatively low, non-invasive sampling methods are likely sufficient for parameterizing the model.

The uninsulated 1.9 cm (3/4 inch) pine plywood cavity and the insulated 1.3 cm (1/2 inch) aspen plywood cavity had slightly higher daily RMSE than the other cavity types and contributed to the highest number of days with RMSE greater than 2°C. Higher error in the uninsulated 1.9 cm (3/4 inch) pine plywood cavity may be attributed to its lack of insulation, making it less thermally stable, and more prone to effects of radiation or convection on cavity temperature than the other artificial cavity types. Nonetheless, differences in RMSE were small among all artificial cavity types, indicating that error caused by differences in plywood thicknesses and plywood tree species were small relative to random effects such as differences in sample size, location of boxes, sampling period length, or other factors that could affect RMSE.

4.1. Thermal arrest periods

We found 40% of days sampled had a period where natural cavity temperatures exhibited a thermal arrest phenomenon, mimicking the fundamental dynamics of phase change described in previous studies (Graf et al., 2015; Zhao et al., 2021). When cavity temperatures reached freeze-thaw temperatures (between -1 and 1 °C), a thermal arrest period began and temperatures in the cavity remained within freeze-thaw for extended periods of time. When a thermal arrest period ended, measured temperatures would then gradually return to expected temperatures in the absence of freeze-thaw temperatures. Because there has not been any documentation of this phenomenon occurring in tree cavities, the exact mechanism of how thermal arrest periods occur in the internal cavity space is unknown. We expect that the mechanism is similar to that of solid trees, where water or sap in the wood undergoes a phase change when temperatures reach freeze-thaw temperatures, creating a thermal arrest period in the wood temperature (Derby and Gates, 1966; Graf et al., 2015; Charrier et al., 2017; Reid et al., 2020; Zhao et al., 2021). For tree cavities, we believe that during this period,

there is an exchange in energy between the water/sap, the wood surrounding the cavity space, and the air within the cavity, resulting in the entire tree cavity system exhibiting a period of thermal arrest. Future work, however, should verify the mechanisms driving the thermal arrest periods we identified in this study.

Thermal arrest periods did not occur in artificial cavities. This could be because artificial cavities maintain drier microclimate conditions than natural cavities (McComb and Noble, 1981a; Maziarz et al., 2017) and therefore may not have enough water content for thermal arrests to occur. Further, construction materials have lower moisture content than green wood in standing trees (Skaar, 2012). The water repellent chemicals in wood preservatives would also result in drier conditions in artificial cavity walls.

The model does not directly account for phase change processes at freeze-thaw temperatures, and therefore cannot predict thermal arrest periods. Consequently, days that had a thermal arrest period had higher daily RMSE and accounted for proportionately more days that had RMSE greater than 2°C. Differences in average daily RMSE between days that had a thermal arrest period and days that did not have a thermal arrest period were less than 0.4°C. There was also a large proportion (69%) of thermal arrest days with RMSE less than 2°C, indicating the model can produce acceptable results at the daily scale during freeze-thaw conditions.

Predicting thermal arrest periods would decrease model error under freeze-thaw conditions. Phase change dynamics in trees, however, are complicated by differences in structure, cells, and tissues within and between individual trees and tree species (Lintunen et al., 2013; Charrier et al., 2017; Reid et al., 2020; Zarrinderakht et al., 2021). Patterns are also influenced by other factors such as microclimate (i.e., temperature and humidity), topography, or how much water or sap is in the system (Graf et al., 2015; Charrier et al., 2017). Reid et al. (2020) described a model that can predict temperatures throughout tree stems using transient heat flow processes. In their model they account for phase changes of water by assigning the sapwood a large pseudo-specific heat capacity when the cavity reaches a specific temperature interval in which phase change is expected to happen. In a simulation they found the model predicted a thermal arrest with little error (RMSE = 0.9 °C). Adapting their technique to the model described in this paper could be useful but may be difficult given that the foundation of our model is based on lumped capacitance energy transfer and not transient energy transfer.

Thermal arrest periods in cavities can affect cavity selection and animal thermoregulation. For example, if cavities remain stable around freeze-thaw while ambient temperatures rise above freeze-thaw, the thermal benefit of thermal arrest periods to animals is lower. Conversely, if ambient temperatures fall below freeze-thaw while a cavity is experiencing a thermal arrest in temperature, an animal would benefit by selecting that cavity. The effect of body heat from an animal would tend to make a cavity warmer (Maziarz, 2019). At temperatures slightly above freeze-thaw, the added body heat would delay or prevent a thermal arrest period. In contrast, at temperatures slightly below freeze-thaw, added body heat could increase the probability or alter the length of a thermal arrest period. Despite a large range and high standard deviation of bias values across the thermal arrest periods, the average bias across all thermal arrest periods was close to 0°C. This indicates that the net thermoregulatory cost of selecting a cavity that experiences multiple thermal arrest periods is close to zero.

4.2. Model applications

The model we describe in this study is a useful tool that allows us to predict a cavity's temperature, providing the opportunity to understand the effects of cavity thermal environment on habitat selection or physiology of cavity-dependent animals. For example, the model can be used to understand the effects of temperature on the development and growth of offspring, or energy needed to regulate body temperature (Kendeigh,

1961; Du Plessis et al., 1994; Zalewski, 1997; Sedgely, 2001; Wiebe and Swift, 2001; Ardia et al., 2006; Clement and Castleberry, 2013; Joyce, 2013; Matthews et al., 2019).

Researchers can adjust the model's input parameters to create different cavity scenarios. For example, the parameters that are associated with the cavity's thermal and physical characteristics can be adjusted to predict temperatures in cavities that vary in size and wood type. Having the ability to adjust model parameters can also be useful for understanding how a cavity's temperature changes over time as its thermal and physical characteristics change through decay, or from cavity excavators (Edworthy and Martin, 2014). Researchers can also adjust ambient temperature conditions and predict historical and future cavity temperatures. This would be especially useful when understanding the direct effects of climate changes on cavity microclimate and associated effects on behavior and physiology of the species that use cavities.

Lately there has been increased interest in using nest boxes as a management tool in areas where natural cavities are limited (Goldingay et al., 2015). For nest boxes to be an effective alternative, they must mimic the overall function and microclimate of the natural cavities in the areas of interest (Griffiths et al., 2018). Researchers can create multiple designs of nest boxes and use the model to estimate the internal temperature and determine which nest box design is best, without having to build and install them and then measure their internal temperature (Goldingay et al., 2015; Larson et al., 2018).

The framework of this model may also be useful for predicting the temperature of other enclosed microsites. For example, the temperature of hollow logs, squirrel dreys, or enclosed nests could potentially be estimated by treating them as a lumped capacitance reservoir of heat and using similar simplifying assumptions we used to model tree cavities. However, other energy processes may play an important role in these systems. Testing and verifying the model on these systems would be needed.

5. Conclusion

The model described in this paper is useful for predicting cavity temperatures. It is computationally simple and easy to parameterize relative to other microclimate models (e.g. NicheMapR). It was generalizable across two study areas, in different tree species, in different cavity sizes, and in natural and artificial cavities. Although we tested this model in cavities used by martens and fishers, the model's ability to predict cavity temperatures across a relatively broad range of conditions should allow it to model temperatures in cavities that are used by other animal species. Further, the thermal model could be a useful tool for ecological applications such as understanding animal response to cavity temperature. For example, researchers can use our model to understand how differences in cavity characteristics influence cavity microclimate and selection by animals. Similarly, our model can be used to predict temporal changes in cavity temperatures, which can be important for understanding cavity use in response to changes in climate.

CRediT authorship contribution statement

Taylor B. Velander: Conceptualization, Methodology, Data curation, Validation, Formal analysis, Writing – original draft, Writing – review & editing. **Michael J. Joyce:** Conceptualization, Funding acquisition, Methodology, Data curation, Writing – review & editing, Supervision. **Angela M. Kujawa:** Conceptualization, Data curation, Writing – review & editing. **Robert L. Sanders:** Conceptualization, Funding acquisition, Data curation, Writing – review & editing. **Paul W. Keenlance:** Conceptualization, Funding acquisition, Writing – review & editing. **Ron A. Moen:** Conceptualization, Methodology, Formal analysis, Writing – review & editing, Supervision.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:[10.1016/j.ecolmodel.2023.110302](https://doi.org/10.1016/j.ecolmodel.2023.110302).

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