UNDERSTANDING THE DISTURBANCE OF HUMAN RECREATION ON WILDLIFE USING MULTIPLE DYNAMIC AGENTS WITHIN AN ABM FRAMEWORK

by

Soraida Garcia

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THE PURDUE UNIVERSITY GRADUATE SCHOOL
STATEMENT OF COMMITTEE APPROVAL

Dr. Patrick A. Zollner, Chair

Department of Forestry and Natural Resources

Dr. John B. Dunning

Department of Forestry and Natural Resources

Dr. Shadi Atallah

Department of Agricultural & Consumer Economics
University of Illinois Urbana-Champaign

Approved by:

Dr. Robert G. Wagner

Dedicated to all the students who face inequities in academia

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ABSTRACT

As the need for outdoor recreation grows, the profound impact of recreational activities upon wildlife is a major concern. For example, the presence of humans may increase risk-averse behavior by wildlife, restricting access to essential resources, and reducing foraging, thereby negatively impacting breeding. Ultimately, the impacts that recreationists have on wildlife include directly or indirectly altering population structure and community composition. Unfortunately, understanding the impacts of recreating humans upon wildlife is a complex challenge that is dependent upon wildlife species and human activity types. Our understanding of human-wildlife relationships can be improved by combining results from empirical studies with simulation models to extrapolate mechanisms to a broader range of circumstances and investigate their implications. Accordingly, we developed an ABM modeling framework, that enables both dynamic virtual human and wildlife agents to change their actions. These changes are based upon their state as a consequence of their interactions with their environment and other virtual agents. A unique aspect of the framework we developed is the explicit simulation of both wildlife and human agent behavior as emergent rather than imposed. We use this framework to model the disturbance of birds, in the Lawrence Creek Forest Unit (LCFU) of Fort Harrison State Park, IN, by human recreation. We parameterize the model with human recreation data collected through an intercept survey of recreationists at the park and bird data from published studies. We compare our modeling framework to a more traditional model type where human behavior is imposed while wildlife behavior is emergent. Our results indicate that the frequency of humans entering the park influences the rates of disturbance of birds more than model types. Examining simulation behavior within our new framework, the utility and off-trail options had the most influence across all scenarios. These comparisons illustrate that the use of a modeling framework that allows managers to explore factors altering wildlife disturbance rates. Despite the marginal influence of model type upon our results, our research elucidates the value of a model that allows emergent behavior for multiple agent types. The emergent human and wildlife responses of simulated interacting agents provides new insight when managing these relationships.

CHAPTER 1. A REVIEW OF RELEVANT LITERATURE UNDERLYING THE HAWAI MODEL FRAMEWORK

Human recreation within outdoor landscapes is growing, and the extent and intensity of the impact of such activities upon the natural systems are increasing (Blumstein et al., 2005). The US National Park systems estimated 331 million visitors during 2016 (DOI, 2016). The infrastructure supporting visits by these recreationists promoted the creation of 295,000 jobs and added $32 billion to the economy during 2015 (Koontz et al., 2017). Globally, Balmford et al. (2015), measured visitation rates to protected areas and estimated 8 billion visits a year, resulting indirect expenditures of approximately $600 billion annually. These increases in recreational activities result in economic growth, but these visits can, directly and indirectly, impact wildlife (Shope, 2020).

Encounters between recreating humans and wildlife may have negative consequences for many wildlife species (Frid et al., 2002). This is a clear and obvious concern when such consequences impact populations of threatened and endangered species. Specifically, the U.S. Endangered Species Act mandates the protection of listed wildlife species (Salau et al., 2015). It does this by prohibiting the "taking" of any listed wildlife species, including the direct or indirect killing of listed species, and safeguarding the viability of habitat for those organisms (US Endangered Species Act, 2001). Furthermore, the harassment of wildlife is also prohibited because it is considered a form of take (DOI, 2016). However, requirements to protect species of concern are challenging when federal agencies are mandated to balance multiple uses of public lands, while complying with environmental laws and regulations (Stein et al., 2008). This combination of responsibilities may pose conflicts between restrictions to protect wildlife and the desire to provide the public with the opportunity to recreate.

The impacts that recreationists can have on wildlife include directly or indirectly altering population structure and community composition (Priotta et al., 2018). For example, wildlife may view recreationists as potential predators, triggering responses similar to that of predator-prey encounters (Frid et al., 2002), such as flight (Taylor et al., 2003). As a consequence, the presence of humans may increase risk-averse behavior by wildlife, restricting the access of wildlife to essential resources (Musiani et al., 2010). Such restrictions may reduce foraging success, thereby having negative implications for breeding (Beale et al., 2004). In contrast, human recreation may have positive impacts on some species. For example, a study by Lunardi et al., (2014) documented that human fishing practices in intertidal areas in Brazil increased foraging success of shorebirds. Thus, understanding the impacts of recreating humans upon wildlife is a complex challenge that is dependent upon the specifics of the wildlife species and human activity types (Hebblewhite et al., 2008). This complex challenge of balancing human recreation and functioning ecological communities requires understanding the cost and benefits for humans and wildlife to inform appropriate management.

Public investment in conservation is ultimately contingent upon natural systems providing things that people care about. Providing access to the natural environment is invaluable because it encourages people to care about the preservation of such green spaces (Gunnarsson et al., 2016). Restricting access to these areas may affect visitor spending that can result in a reduction of the park system's economic contribution to state and local community (Koontz et al., 2017). If the magnitude of such restrictions became large enough, they may ultimately reduce or undermine public support for conservation resulting in decrease in appreciation for the natural world (Aldous et al., 2007). This can create a negative feedback loop that further diminishes public wellbeing and wildlife conservation.

Management of the conflict between recreating humans and wildlife may be more complicated when the green space in question is embedded within an urban matrix rather than other land use types. This is especially important in areas that are becoming more urbanized, which is a growing trend (Hörnsten et al., 2000). More than 55% of the world's population inhabits urban areas (United Nations 2018, Schultz et al., 2019), and this percentage is expected to grow to 68% by 2045, according to the United Nations Department of Economic and Social Affairs. As the density of humans increases in developed areas, the availability of green spaces typically decreases (Gallo et al., 2017), putting more of a premium on the small remnants. In urban centers you find more people exerting more influence on political and economic systems. Unfortunately, it is common that people in these urban environments are more disconnected from nature. Furthermore, the wildlife species found in urban environments are typically not species of conservation concern. So, these trade-offs between human recreation and wildlife distribution, may be fundamentally different in urban green spaces. The majority of research investigating conflicts between human recreation and wildlife occurs in remote parks and systems far from urban settings. Therefore, there is a critical need to learn and investigate how the mechanisms underlying these interactions and outcomes differ in urban settings. Developing this understanding is invaluable because managers of green spaces in urban environments may need to use different tools and have the opportunity to impact the lives of many human beings.

To minimize conflicts between recreating humans and wildlife, managers employ a variety of strategies such as fencing and signage. Buffer zones are one of the most effective management strategies (Rodgers et al., 2002, D'Acunto et al., 2018, Salgueiro et al., 2019, Wallace et al., 2016). This approach involves limiting the proximity of recreational activities to important habitat for wildlife species of concern. Another successful strategy is the use of fencing to prevent access to unprotected habitat (Ikuta et al., 2003). Current trends in the literature suggest that using a combination of multiple management methods, such as regulating the number of visitors allowed on trails, limiting access, and having an authoritative figure on site, (Marschall et al., 2017, Hockett et al., 2017, Park et al., 2008, D'Antonio et al., 2017) is the best way to alter visitor behavior. For example, a study by Kidd et al., (2015) used Global Positioning System to track the behavior of visitors on and off-trails, in Sargent Mountain in Acadia National Park, Maine. They found that the combination of information given to visitors via personal contact by an authoritative figure along with trail markers was more effective at keeping visitors on trails than the posting of signs alone.

A common approach to understanding the impacts recreationists have upon wildlife involves measuring behavioral responses of wildlife to human disturbance. A broad range of these types of studies have been conducted using experimental (Blumstein et al., 2016) and observational (Bateman et al., 2017) procedures. A typical response variable for both types of studies is to measure flight initiation distances by observing wildlife reaction to recreational activity from a remote and hidden location (Boetsch et al., 2018, Whitfield et al., 2008, Sirot et al., 2010). Experimental studies are distinguished because they employ humans to emulate recreation in controlled patterns (Arlettaz et al., 2015, Rodriguez-Prieto et al., 2005, Bennett et al., 2013). For example, an experimental study conducted by Fernandez-Juricic et al. (2007), analyzed the behavioral responses of Black-crowned Night Herons (Nycticorax nycticorax), to recreational activity by intentionally paddling canoes in and around bird colonies. Such observational and experimental studies have been conducted across the globe in Africa (Arbieu et al., 2018), Antarctica (Coetzee et al., 2016), Asia (Paudel et al., 2012), Australia (Schlacher et al., 2013) Europe (Granquist et al., 2016), North America (Johnson et al., 2005), and South America (Barros et al., 2014). Furthermore, this research has occurred at habitat types ranging from intertidal mud flats (Hamza et al., 2015), through mature forests (Drapeau et al., 2000), and even as remote as glaciers (Stafl et al., 2015).

Our understanding of human-wildlife relationships can be improved by combining results from empirical studies with simulation models to extrapolate mechanisms to a broader range of circumstances and investigate their implications (Gao et al., 2014). This combination provides unique perspectives and insights to inform management decisions and resolve conflicts. Agent Based Models (ABM) are tools that use adaptive agents to simulate interactions between those agents and their surrounding environments as well as each other. Such models can be used to simulate a range of input parameters and model structures (Garcia et al., 2005). By comparing the output across such a suite of scenarios to observed empirical patterns and determining which model predictions best match reality, we can gain important insights into the mechanisms underlying system behavior (Liu et al., 2019).

SoDA (Simulation of Disturbance Activities) is an ABM framework that simulates human disturbance of wildlife (Bennett et al., 2009). It has been used to inform management decisions in efforts to preserve wildlife habitats (D'Acunto et al., 2018) for taxa such as bats (Bennett et al., 2013), birds (Rodriguez-Prieto et al., 2014), and butterflies (Bennett et al., 2013). In SoDA, the virtual wildlife are dynamic (meaning they have flexible rules that change their behavior as a function of their state and context), but the human recreational activity is imposed and static (meaning simulated humans behave in a preprogrammed manner which is fixed without considering state or context). The user creates GIS layers to describe polygons that form different habitat types. Within the habitats, point and line files are implemented representing areas of interest such as roosting locations and trails. Within this environment rules delineate agent's direction and speed of movement. Ultimately, the model is used to understand the response of virtual wildlife species to different forms of human activity as represented by simulated scenarios. An important limitation of SoDA is the static imposed behavior of simulated human agents which restricts them from exhibiting the dynamic responses that the model grants virtual wildlife agents. This makes SoDA less relevant to real-world circumstances where humans are likely to alter their behavior in response to their experiences within the recreational environment.

HaWAI is an ABM framework that has been developed to address SoDA's shortcoming of imposing behavior on human agents (Figure 1.1). HaWAI emulates the structure of SoDA while enabling both virtual wildlife and human agents to change their behaviors based upon their state as a consequence of their interactions with their environment and other virtual agents. Traditionally, ABMs are used to simulate one type of sophisticated agent's interaction with the virtual environment around it and other individuals of that same type (Chen et al., 2015). Such a focus upon a single agent type helps ensure that models are simple enough to be able to interpret their complexity, keeping their design well within the "Medawar Zone" (Grimm et al., 2004). The foci of these ABMs on a single agent type are fundamentally limiting because many real-world conflicts involve interacting sets of different types of agents that are all sophisticated and intelligent. Some authors have acknowledged the potential for ABMs to become more meaningful and relevant if they were used to simulate such interactions between multiple types of smart agents (Macy et al., 2002). The disturbance of sensitive wildlife species by recreating humans provides an example of circumstance in which the behavior of the overall system is an emergent consequence of the interactions of dynamic wildlife and humans responding to each other's choices. My Masters' thesis uses the modeling framework HaWAI to demonstrate how model predictions vary when both virtual wildlife and virtual humans are endowed with dynamic sophisticated capabilities.

The goal of this research project is to demonstrate how having multiple types of dynamic agents in ABMs can change model outcomes. The chapter that follows simulates scenarios of recreational management in an urban park using intelligent dynamic human and wildlife agents. My objective in chapter 2 is to investigate how the predicted impacts upon bird species of recreating human agents in Fort Harrison State Park change when the virtual humans are endowed with the range of capabilities that SoDA provided to virtual birds in a previous investigation (Rodriguez-Prieto et al., 2014). These investigations will illustrate the value of simulating multiple types of dynamic interacting agents and demonstrate a better approach to understanding what happens in human wildlife recreation disturbance scenarios. Collectively, this improved understanding should present managers with new perspectives on how to respond to the challenging circumstances they face in balancing trade-offs between human recreation and the conservation of wildlife species.

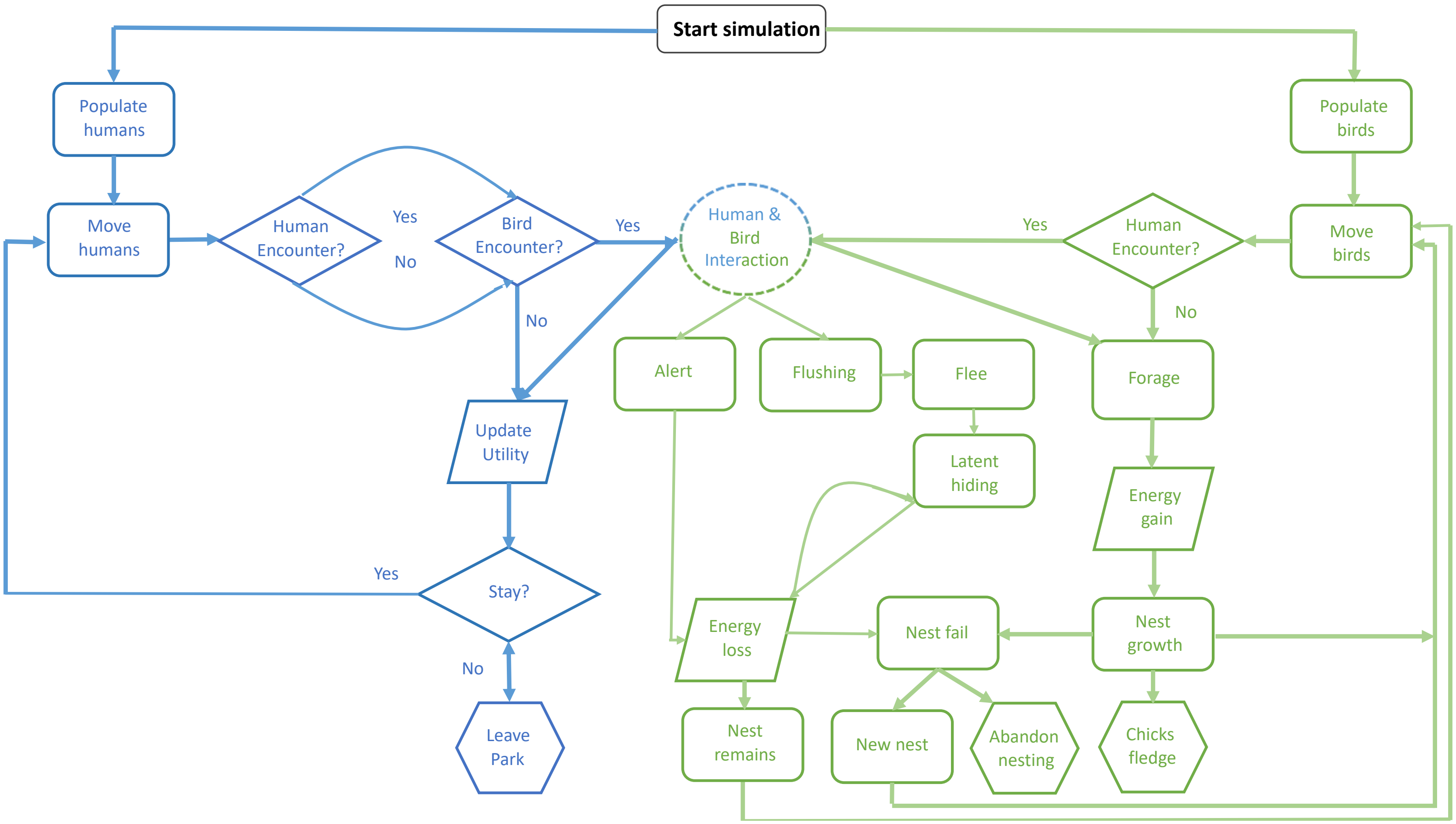

Figure 1.1: HaWAI framework flowchart demonstrating the synchronized simulation process of human recreationists (blue) and bird agent behavior (green). Direction of arrows indicate the flow of decision making and behavior or action taken while making one complete simulation run. Humans move through trail interacting with other humans or birds accumulating utility with each timestep eventually deciding to leave the park or stay. Birds interact with humans becoming alert or flushing while losing energy resulting in nest failure, abandonment or persistence. If no interactions with humans occur, birds forage and gain energy creating nestling growth.

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CHAPTER 2. A SIMULATION OF SCENARIOS USING MULTIPLE AGENTS TO COMPARE THE IMPACTS OF DISTURBANCE ON BIRDS BY RECREATING HUMANS

Abstract

The increase demand for outdoor recreation gives green spaces added value within urban areas. Continual use of these spaces can critically impact shared environments used by recreationists and wildlife. Understanding the interaction of human recreation and wildlife is critical when discovering the consequences of these impacts (Hebblewhite et al., 2008). Such impacts can alter population structure and community composition (Priotta et al., 2018). This can be a challenge as the effect of these impacts are influenced by both the characteristics of the wildlife species being disturbed and the type of human recreationist activity. Therefore, we need effective tools to investigate mechanisms of interactions of these systems. We developed an agent based model (ABM) that simulates the disturbance of human recreation on wildlife located within the Lawrence Creek Forest Unit (LCFU) in Fort Harrison State Park, IN. This model is an expansion of a previous study that examines the disturbance of birds by imposing human recreation behavior (Rodriguez-Prieto et al., 2014). To investigate any underlying mechanisms that impact the disturbance of birds, we further explored the tool by adding a range of input parameters collected from an intercept survey at LCFU. Our results indicate the disturbance of birds was more influenced by the number of simulated humans than by the emergent or imposed behavior of those humans. Further investigation of results from the model with emergent human behavior demonstrated that human movement off established trails had the largest effect on the birds, compared to other human behaviors. Among recreationist type, jogger's utility most strongly influenced bird disturbance of all species. Utility is the satisfaction a recreationist receives from performing a recreational activity. When measuring change in recreationist utility, off-trail and utility guard were the most important variables across recreationist types. Our study indicates that the frequency of disturbance is more important to birds than the type of recreationist causing the disturbance. Furthermore, the relative importance of different factors on the disturbance of birds differed between our model results and the responses recreationists gave during the intercept survey. The actions of recreationists, such as going off-trail, weighed more on the disturbance of birds than their opinions of other recreationists. The approach we developed illustrates how

simulating multiple adaptive agents can provide valuable insight on the underlining mechanisms contributing to bird disturbance which is useful to the conservation of wildlife.

2.1 Introduction

Human recreation within outdoor landscapes is growing, and the extent and intensity of the impact of such activities upon natural systems is increasing. Where greenspace is limited, increasing demand for outdoor recreation makes it highly valued and sites providing this recreation are visited regularly. The U.S. National Park System estimated 327 million visitors to their properties during 2019 (DOI, 2019). Globally, Balmford et al., (2015), measured visitation rates to protected areas and estimated 8 billion annual visits. Such use of green space can dramatically impact many of the characteristics of the sites. For example, frequent human visitation can, directly and indirectly, impact wildlife (Shope et al., 2020). Such impacts can alter population structure and community composition (Priotta et al., 2018). Mechanisms underlying these impacts include wildlife exhibiting anti-predatory responses to human activity. These responses trigger behaviors such as flight (Taylor et al., 2003). As a consequence, the presence of humans increases risk-averse behavior by wildlife (Musiani et al., 2010) resulting in restricting access to essential resources. This makes understanding the impacts of human recreation upon wildlife more important (Hebblewhite et al., 2008). This complex challenge is strongly influenced by both the species of wildlife being disturbed and the type of human recreationist causing the disturbance as well as the characteristics of the natural area. Therefore, we need effective tools to investigate the mechanism of interactions of these systems. Such tools will provide insights into managing relationships between human recreation and wildlife.

Agent Based Models (ABMs) can provide insights into the relationships between human and wildlife but results can be sensitive to model structure which is often a function of the relative complexity of model design. These tools simulate interactions between: adaptive agents, the surrounding environment, a range of input parameters, and model designs (Garcia et al., 2005). In such investigations, we can gain important insights into the mechanisms underlying system behavior by comparing output across a suite of scenarios to observed empirical patterns and determining which model predictions best match reality (Liu et al., 2019). For example, ABMs simulated agents can range dramatically from very simple rule sets to highly sophisticated ones. The appropriate degree of complexity that agents are endowed with is primarily a function of the questions asked. Many models focus upon the implications of the rules given to a single agent type (Chen et al., 2015). Focusing upon a single sophisticated agent type helps simplify models so that it is easier to keep the model design well within the "Medawar Zone" (Grimm et al., 2004). This zone optimizes model functionality along the gradient from simple to highly complex models. However, focusing on a single agent type is limiting because many real-world problems involve interacting sets of different types of agents that are all sophisticated and intelligent. For certain questions ABMs can become more meaningful and relevant when simulating such interactions between multiple types of smart agents (Macy et al., 2002). This is likely to be true when the interactions of dynamic human and wildlife agents cause the behavior of the overall system to emerge as a consequence of these two agent types responding to each other.

SoDA (Simulation of Disturbance Activities) is an ABM framework that simulates human disturbance of wildlife (Bennett et al., 2009). It has been used to simulate a wide variety of species: butterflies, eagles, bats (Bennett et al., 2013, D' Acunto et al., 2018, Bennett et al., 2013) in a wide variety of places. A previous investigation (Rodriguez-Prieto et al., 2014) used SoDA to model how recreational activity disturbed populations of bird agents at the Lawrence Creek Forest Unit (LCFU), Fort Harrison Park, IN. The results provided the Indiana DNR with insights regarding the protection of resident bird populations while maintaining recreational use. However, SoDA is limited because it imposes static behavior on simulated human agents unlike the sophisticated dynamic behavior with which SoDA endows wildlife agents. This limitation restricts the ability of SoDA's virtual human agents to respond to their experiences within the recreational environment. Such restrictions often have their origins not only in model design but also in the lack of information to parameterize human behavior. The paucity of data related to the impacts of human recreation on wildlife behavior constrains many studies of this type. This constraint limits the capability to extrapolate mechanisms to a broader range of circumstances and investigate their implications (Gao et al., 2014).

Understanding human-wildlife relationships can be improved by combining results from empirical studies with simulation models (Beale, 2007). Social scientists from Purdue University conducted an intercept survey at Fort Harrison State Park during the summer of 2015 (Radulski et al., 2019). This survey quantified the opinions of recreationists who encountered birds and other recreationists within the LCFU. Integrating these survey results with bird data into the established SoDA parameterization may change predictions and insights from this model. Doing so will demonstrate implications of simulating the interactions of intelligent human and wildlife agents within a single model.

The failure to endow both human and wildlife agents with dynamic rules could obscure important interactions between these agent types. The obfuscations of such interactions may provide different guidance regarding the impacts of modeled scenarios for some species. In this study we develop HaWAI (Human and Wildlife Adaptive Interactions), an ABM framework, and demonstrate how it addresses these shortcomings. HaWAI emulates the structure of SoDA while enabling both virtual wildlife and human agents to change their behaviors. These changes are based upon their state as a consequence of their interactions with their environment and other virtual agents. Our objective is to model how human recreation disturbs the birds in the LCFU. We hypothesize that the dynamic human agents interacting with dynamic wildlife agents in the HaWAI modeling framework will change modeling outcomes compared to previous models with static human behavior. If the above hypothesis is true, we predict that all else being equal, the rates of disturbance of birds, and the energy provided to nesting birds, will be differ between SoDA and HaWAI. Secondarily, we hypothesize that within the HaWAI model the disturbance rate of birds will be a function of the interaction of bird species sensitivity to human activity and recreationist type. If this hypothesis is true, we predict that within HaWAI, sensitive bird species will be disturbed significantly more frequently than insensitive bird species by jogger and birder agent types.

2.2 Materials and methods

2.2.1 Study site and data set

Our study simulates human recreation and wildlife activity located within the LCFU on the west central side of Fort Harrison State Park, Indiana. This area consists of a 4.8 km multi-use trail that runs around the perimeter of the unit. Recreationists using trails in LCFU include bikers, hikers, joggers and birders. Data on the use of the LCFU by these recreationists was collected through an intercept survey at Fort Harrison State Park (Radulski et al., 2020). This survey assessed recreationists' opinions of encounters with birds and other recreationists within the LCFU. The survey also assessed the frequency of visits to the LCFU and time spent on trail by all recreationist types. However, no birders were encountered during the intercept survey. Records of birders using the LCFU from E-Bird were used to identify birders and solicit their responses. Responses from the survey showed the amount of time each recreationist type estimated they spent in the park. Results showed that bikers and birders estimated their use of the park was greater than that of hikers and joggers. The analysis of data collected from humans who recreated within LCFU documented that birders expressed more concern about encounters with other recreationist types and veered off-trail more frequently while joggers were the recreationist type least sensitive to the activities of other humans in the park.

I simulated the responses of nine bird species to human recreation in LCFU. These are the same species that Rodriguez-Prieto et al. (2014), modeled within the LCFU using the SoDA framework. They parameterized their virtual birds with data from published studies that described the behavioral response patterns of study species or similar surrogate species. For some species, Rodriguez-Prieto et al. (2014) directly measured bird behavior in LCFU. I used the same parameter values as inputs for these bird species in my modeling. The nine modeled bird species represent gradients of sensitivity to human disturbance, and relative local abundance. The 9 specific species and the characteristics that describe them are presented in Table 2.2.

2.2.2 Modeling Framework

SoDA is a modeling framework that simulates the behavior of wildlife agents when human disturbance is imposed (Bennett et al., 2009). It creates a virtual environment that can be modified by the user. It works with GIS maps that input habitat components such as the location of nests, trails and cover types. Variables emulating human characteristics and wildlife responses are parameterized for the respective agents within the model. Wildlife agents within SoDA are endowed with rules for how they interact with human agents. These interactions make wildlife agents within SoDA more sophisticated than its human agents. More specifically, human agents in SoDA only interact with the landscape and not with other human or wildlife agents. The SoDA simulation produces output useful to understand human disturbance of wildlife (Rodriguez-Prieto et al., 2014) such as changes in behavior, movement patterns, energy levels, mortality rates, and breeding success in response to human activity.

HaWAI is a modeling framework designed for investigations of interaction between dynamic human and wildlife agents in a recreational environment (Figure 2.1). HaWAI is built upon the same design concepts as SoDA with new capabilities. HaWAI was coded in NetLogo, a programming platform for building ABMs (Grimm et al., 2013). HaWAI outputs include the amount of overall bird disturbance, mean number of times birds become alert or flush, fate of each nest (succeed or fail), number of disturbances caused by each type of recreationist, average duration of disturbance, frequency and number of human present, utility of each recreationist type during each timestep, number of recreationists leaving the simulation early or late, and average duration each recreationist spends in park. Below I provide an ODD (overview, design concepts and details) description of the HaWAI model according to criteria established in Grimm et al., 2020.

2.2.3 ODD description of HaWAI model

Purpose

The HaWAI modeling tool simulates the interaction between human recreationist and wildlife agents endowing both sets of agents with sophisticated rules for how they respond to each other. This is an advancement of the SODA foundations from which HaWAI was developed (Bennett et al., 2009).

Entities, state variables, and scales

My application of HaWAI to the LCFU involved the creation of human agent types and parameterization of their characteristics that defined them. There are four types of entities: birds, humans, patches and trails. The HaWAI model represented human agents moving along trails within the LCFU. Virtual bird agents foraged near their nests and reacted when approached by human agents. Nine virtual bird species were simulated: Downy Woodpecker (*Dryobates pubescens*), Eastern Wood-Pewee (*Contopus virens*), Acadian Flycatcher (*Empidonax virescens*), Carolina Chickadee (*Poecile carolinensis*), Brown Creeper (*Certhia americana*), Wood Thrush (*Hylocichla mustelina*), Kentucky Warbler (*Geothlypis formosa*), Hooded Warbler (*Setophaga citrina*), and Ovenbird (*Seiurus aurocapilla*). Virtual nest locations were generated stochastically based on probabilities derived of each species nesting within each habitat type. Patches were either bird habitat or trail type. Habitat patches were characterized as one of four categories: relict forest or young forest with dense honeysuckle present or absent in the understory. A raster representing the LCFU was created in ArcGIS and imported into NetLogo. Trails in the LCFU were named

South, North, East Access or Camp Glenn. Human recreationists were bikers, birders, joggers, or hikers. Humans were parameterized to behave either in a non-adaptive manner like agents in SoDA or in an adaptive manner that takes advantage of HaWAI capabilities. Within SoDA humans appeared at random locations on the trail, persisted for one timestep, and disappeared at a frequency that emulated the desired density of recreationist activity for each replicate. Within HaWAI, adaptive humans began the simulations at trailheads and persisted for multiple time steps as they move down trails. While moving down trails these agents exhibited a variety of behaviors such as bird watching. These same humans assessed their experience using a function that changes their utility based upon encounters with other human agents influencing the duration of their stay in the park. Each cell of the virtual environment represented a 2m x 2m area of the LCFU.

Process, overview, and scheduling

The HaWAI model simulated a 21-day breeding period for the bird species in the model. One full simulation represented 30240 timesteps which equaled 1440 timesteps per day. Each simulated timestep represented 1 minute of real-world time. Throughout the simulation virtual recreationists entered and left the park based upon empirically derived rules for each recreationist type. For example, birders recreated earlier in the day to view birds while the frequency of simulated joggers went up during the afternoon to early evening. This was accomplished by assigning each type of recreationist a probability distribution for using the park as a function of time of day. The user of the model specified the minimum number of recreationists (of all recreationist types) that were simulated at any given time. For this application of HaWAI we ran replicates within this maximum set to 40, 60, or 90 recreationists per day. The user specified a number of individual bird species to occur in the model. During each simulation virtual birds slept at night while during the day they switched between foraging, became alert, and flushed in response to human activity. Those individual bird species were randomly assigned nesting locations within species-specific preferred habitat types. Those virtual birds foraged in proximity to the nest and were disturbed when they encountered virtual humans. If the nest failed because disturbance levels were too high, the bird was assigned to a new nest, maintaining the targeted bird population densities. As virtual recreationists encountered other agents, they updated a state variable estimating the instantaneous utility of their visit to the LCFU. Every 10th timestep virtual recreationist evaluated their current utility level and if that exceeded a threshold they either began moving along the trail towards a trail head to leave the simulation or extended the duration of their visit in the LCFU. All else being equal, birds spent their active time during the day foraging but if humans approached they became alert, would not forage while remaining vigilant. If recreationists moved close enough to exceed a second threshold the birds fled, reevaluated their energy levels and decide to return to their nests or let it die.

Check-time-of-day

Controlled bird circadian rhythms, human density, and recreationist type by time of day.

Manage-humans

If human-type is SoDA, humans entered and left a simulation according to the time of day as was done in the SoDA study (Rodriguez-Prieto et al., 2014). If human-type is Adaptive, this was the HaWAI version of the model with humans possessing adaptive traits. Specific human agent types entered the simulation according to the time of day and exhibited the following traits: caused disturbance, watched birds, stalked birds, moved along trails, lengthened or shortened duration of stay, had negative or positive encounters with other humans, and varied speed.

Track-encounters

Tracked the number of encounters with other recreationists, from behind and head-on, updated counters for both recreationists. For each time step, each virtual agent assessed how many other virtual human agents it encountered of each type during that time step. These encounters update the total number of other agents of each type encountered for that agent. Virtual bird agents responded appropriately by becoming alert or fled if their proximity to human agents exceeded thresholds. Virtual human agents updated their current utility value based upon their encounters with other human agents and bird agents. Finally, at every 10^{th} tick, these human agents assessed their new utility and adjusted their intended time spent within the park.

Check-guard-on/off

When human agents passed within the user defined threshold of proximity to other human agents, the program checked to see if the user selected guard option to be on or off. If guard is on, then encounters with other human agents did not alter that agent's current utility. If guard is off, encounters with other agents changed that agent's utility.

Cause-disturbance

During each tick each virtual bird assessed if any human agents moved closer than that species alert distance or that species flight initiation distance. If human agents were closer than the alert distance but still greater than flight initiation distance, the virtual bird's state changed to alert for that tick. If a virtual human was closer than the species flight initiation distance during a tick, that virtual bird fled. Finally, each virtual bird's total number of timesteps in the state alert or the state fleeing was updated every 10^{th} timestep.

Bird-watch

During each tick, each human agent had a stochastic probability of detecting any bird within a specified proximity. The probability of detection and radius within which detection might occur varied according to the recreationist type. When birds were detected, human agents updated their utility. These changes in utility may stochastically cause human agents to stop and watch a bird, potentially stalk a bird, and change the duration of their stay in the park. The probability of these various responses to encounters with bird agents varied by human agent type.

Stalk-bird

For every bird detected, each recreationist type had a probability of stopping and watching that bird. If the off-trail switch is on, human agents had a stochastic probability of moving off-trail halfway towards a bird. The duration for which human agents remained at that point, bird watching, varied between human agents. Multiple agents could simultaneously watch any simulated bird. Based upon these encounters with birds, human agents updated their utility which in turn altered the duration of their intended stay within the park.

Resume-movement

After stalking or watching a bird, human agents returned to the place on the trail where they encountered that bird and resumed movement in the same direction. The only exception to this is if the encounter reduced the human utility to a level they intended to leave the park as soon as possible. Under those circumstances human agents reversed direction on the path if it expedited departure from the park.

Calculate-utility

Utility value for each recreationist is determined by: their encounters with birds, their encounters with other human agents of various types, their trail preference, and the typical duration of a park visit for a recreationist of each type. During each timestep, the remaining expected duration of the user's visit is decreased by 1 minute. Expected durations are also updated each timestep as a function of encounters with other agent types that influenced the human agent's experience.

Manage-birds

In the absence of human agents, the model simulated the foraging and activity of birds according to the following algorithm. When foraging, birds chose a direction to move based on a simple correlated random walk (changed their heading up to 90° in either direction from their previous heading) and moved 6 meters in that direction. Following movement, birds gained 0.2 units of energy. When birds reached 15 or more units of energy, they returned to their nest, where energy was transferred until the bird only retained 10 units of energy. When animals moved home, either to deliver energy or to sleep at the end of the day, they moved at a rate of 100 meters per timestep towards their nest location, or directly to their nest if they were within 100 meters. If birds were not disturbed, their behavior depended on the time of day and their energetic status. If birds had an encounter with a human agent during a timestep, the following additional rules altered bird movements. If any human agent came within that bird during that timestep, the bird changed its status to alert. If the proximity of the human agent became closer than flight initiation distance then the bird flushed. If birds become alert to a disturbance, it stayed at its current location and if flushed it moved away. If alert, birds had no change in energetic status; if flushed, they lost 0.1 units of energy. At the end of this procedure, bird behavior was finalized, disturbance trackers were updated, and birds moved or foraged.

Check-nest-failure

The model could be run with user selecting the option to turn nest fail on or off. If nest fail was turned on, nests failed when the energy accumulated by the adults and provided to the nest fell below a species's specific threshold. If nests failed, adults immediately found a new home location and a new nest was created. Re-nesting ensured consistency in the number of simulated individuals of each species. If the user selected the nest fail off option, the simulation kept track of the accumulated energetic status of each nest without ever causing any virtual nest to fail.

Determine-threat-type

When a virtual human agent came within alert and flight distance of a virtual bird, then the virtual bird checked the recreationist type of the human and responded appropriately. These responses included alert or flee as described above. The birds also checked the number of units of energy foraged and updated their cumulative number of alerts and fleeing responses.

2.2.4 Design Concepts

The HaWAI model was designed to simulate the interaction of recreationists and birds while exhibiting behavior on the trail in LCFU. The following key principles described the basic concepts and captured the conceptual characteristics of the model.

Basic principles

The LCFU was used by both birds and recreating humans. The survival of birds within the LCFU depended on the surrounding environment for food resources for themselves and to feed their young as well as protection from predators. Recreating humans visited the LCFU daily to view wildlife and enjoy the surrounding natural system. While on the trail, humans interacted with birds by stopping to watch them. When humans encountered other humans, the quality of each recreationist's experience in the park changed based upon their relationships with those other types of recreationists interactions between recreating humans and birds using multi-agent types on a trail network.

Emergence

Cumulative bird disturbance, bird nesting success and the duration of recreationists visits to the park emerged from the synchronized process of adaptive interactions amongst agents within the LCFU.

Adaptation

In response to approaching human agents, bird agents first became alert and with increasing proximity flushed. These alert and flushing responses were exhibited by real birds seeking to minimize their risk from humans as perceived predators (Frid et al., 2002). Time spent alert and flushing reduced foraging opportunities for birds which could result in nest failure. In HaWAI these responses were represented by simple rules that caused virtual bird agents to stop foraging or flee depending on the proximity of human agents.

Encounters between human agents and other agent types increased or decreased each agent's instantaneous utility. Changes in utility caused virtual humans to remain in the park longer or leave earlier depending upon specific values. Additionally, when humans encountered birds, human agents may stochastically veer off the trail to increase their own utility. Such excursions could further disturb bird agents.

Fitness

The fitness of birds and humans within the LCFU were assessed differently. Bird foraging success and nest survival were essential to achieve fitness. Birds that avoided encounters with humans had more time to forage resulting in higher fitness. The fitness of human agents was assessed as utility. Utility of human agents was strongly influenced by their encounters with other recreationists and birds while on the trail. During each timestep utility was calculated using a cumulative additive log utility function.

Sensing

Both bird and human agents sense other human agents and responded to them. Birds sensed when a human was within alert or flushing distance and responded accordingly. Human agents sensed when another human agent was ahead of them on the trail and sped up to pass them. Human agents were passed, slowed their speed to increase the distance between them and the agent that passed them. All recreationists had a stochastic probability of sensing any birds within a 15-meter radius. When a virtual bird was detected, human agents had a stochastic probability of stopping to watch that bird.

Interaction

Birds interacted with human agents that came within alert distance by becoming alert or that came within flight initiation distance by fleeing. Such disturbances occurred more frequently when the user allowed human agents to leave the trail to observe bird agents they had detected. Human agents interacted with each other by passing each other on the trail while recreating. Humans interacted with the environment by adjusting their instantaneous utility rate as a function of the characteristics of the trail segment they were moving along.

Stochasticity

The following modeled processes employed stochasticity: locating nests within habitat types, foraged success between locations, direction recreationists moved along trails at intersections, time of day recreationists entered the simulation, probability humans detected a bird within a 15-meter radius, probability humans stoped to watch birds they encountered, and probability humans remained within the park or left early.

Collectives

The maximum number of human agents in any one simulation run could be 40, 60 or 90 and represented the human agent collectives in the model. When interacting with other human agents, they may have exhibited negative feedback based on the type of recreationist they encountered. If the threshold of 3 bad timesteps was reached, the agent left the park and a new agent appeared. The new agent entered the simulation based on a probability of that agent's time of day preference. During each simulation run nine bird species were present (107 individual birds) representing the bird agent collectives in the model. Bird agents did not interact with each other but interacted with human agents and the surrounding environment. The emerging behavior of bird agents was the consequence of the agent's interaction with human agents and accumulative energy from one simulation run.

Observation

The following processes were used to observe the internal dynamics of the model: mean number of timesteps birds are alert and fleeing, mean number of timesteps birds are disturbed by each recreationist type, number of nest failures, length of stay for each recreationist, and average instantaneous cumulative utility for each recreationist type. Analysis of effect size was then used to estimate the relative influence of many aspects of model design upon the above response variables.

2.2.5 Initialization

During simulation setup, the virtual environment was created. An input raster of the LCFU was read in and each virtual cell was assigned a habitat. State variables associated with these habitat types influenced the probability of birds capturing food at different locations on the map and when cell habitat types were trails, other state variables determined the preference of human recreationists of different types for the corresponding trail preference. Once the environment were complete, 107 individual birds of 9 species were added to the map. Birds were placed at a randomly selected nesting location within their preferred habitat. A single bird was modeled at each nest location so that its subsequent foraging movement around that nesting location represented potential opportunities for disturbance. Input values for parameters defining state variables of virtual bird species were read from the code such as rarity. Similarly, the input parameter values for each type of human recreationist were read from the code for their state variables such as time-budget or speed.

2.2.6 Submodels

Table 2.1 lists the model parameters for the simulated submodels. Values used were dependent on the model simulated and user selected option.

2.3 Modeling Application

The HaWAI modeling framework was parameterized from the empirical data collected from the LCFU. Values and rules used for virtual birds and maps were based upon those implemented in previous SoDA research (Rodriguez-Prieto et al., 2014). Fortunately, during the summer of 2015, social scientists within Purdue's Department of Forestry and Natural Resources conducted an intercept survey at the LCFU. The human agents within HaWAI employed behaviors based on the survey data, when interacting with each other on virtual trails. For example, recreationists responded differently (stay longer or leave earlier) when interacting with agents of a different type (e.g., birders to bikers, birders to hikers). Also, depending on recreation type, agents responded differently when interacting with birds (e.g., birders probabilistically stay at a location longer).

The environment modeled within this application of HaWAI was within the LCFU, nesting locations for all bird species, and characteristics of recreating agents (hikers, bikers, joggers, birders). I ran additional models to determine which recreational activity had the most influence on overall bird disturbance. Furthermore, HaWAI had an off-trail capability which allows virtual recreationists to veer off-trail and a nest fail option that counts the number of nests that had failed due to human disturbance. For this application I simulated two new recreationist types joggers and hikers. Finally, I modified utility rates for each recreationist type to determine how doing so changed the disturbance of birds between scenarios. A detailed description of each model parameter and the levels of that parameter that I simulated can be found in Table 2.1.

Five replicates of each model scenario (Table 2.3) were simulated. Each replicate run simulated 21 virtual days to represent the mean breeding time of the simulated bird species (Poole et al., 2005). The output from scenarios were compared to the SoDA model to find any change in bird disturbance rates associated with the inclusion of adaptive human agents. Outputs generated by this application of HaWAI that were analyzed and presented as response variables in Table 2.3 assessed bird disturbance, nesting success, and measures of the utility of the experience of the different types of human recreational agents.

2.4 Data Analysis

A general linear model, was used to assess the relative impacts of all predictor variables (Table 2.4) upon each response variable (Table 2.3). Eta squared was used to measure the effect size of each predictor variable on the response variables. Given the potential for large sample sizes leading to spurious inference (Lin et al., 2013), p-values were not interpreted, instead effect size associated with each factor provided relative inference about the impact of each on model results.

2.5 Results

Disturbance of birds was more influenced by the number of simulated humans than by use of model types SoDA or HaWAI. Nest failure eta squared value for total humans was much higher than for model type (Table 5). For the sum of disturbance of all species, the eta squared value for model type increased over that of the value for each individual species (Table 5). For individual species, the total number of simulated humans showed the highest effect size for Carolina Chickadee, Brown Creeper and Downy Woodpecker. The effect size of numbers of humans was greater than that of model type for Ovenbird, Hooded Warbler and Wood Thrush but by a much smaller magnitude. Contrary to this trend, effect size of model type was higher than that of total humans for Acadian Flycatcher, Kentucky Warbler and Eastern Wood-Pewee albeit both effect sizes were of very small magnitude for these species. Interestingly, Carolina Chickadee and Downy Woodpecker disturbance rates differed between model types only when 40 total humans were simulated per run. Increasing the maximum number of humans per simulation run to 60 or 90 diminished the difference between SoDA and HaWAI models appreciably for these species (figure 2.2). When comparing nest failure rates across all species between SoDA and HaWAI models, differences were observed when either 40 or 90 humans were simulated but not at 60 (figure 2.3).

The unique structure of the HaWAI model suggested the importance of investigating the influence of several predictors within HaWAI upon the disturbance of birds independent of comparisons between it and SoDA. Within HaWAI results, we found that the off-trail variable was the most influential (figure 2.5). The off-trail variable had the highest effect size for Carolina Chickadee, Downy Woodpecker, and Hooded Warbler, and an intermediate effect size for Acadian Flycatcher and Ovenbird. Total number of simulated humans had a high effect size for Carolina Chickadee and Brown Creeper and an intermediate effect size for Hooded Warbler, Downy Woodpecker and the sum of disturbance of all species. However, utility guard turned on or off had the lowest effect size on the disturbance of all species except Brown Creeper. When comparing the impact of the utility of different recreationist types upon bird disturbance, we found that jogger's utility most strongly influenced bird disturbance with a high effect size for the cumulative disturbance of all species and an intermediate effect size on Eastern Wood-Pewee, Wood Thrush, Kentucky Warbler and Hooded Warbler (Table 2.6). Birder's utility had an intermediate effect on the disturbance of Wood Thrush and the cumulative disturbance of all species variables. The interaction of jogger utility and total number of humans had an intermediate effect on disturbance of Ovenbird. The interaction of biker and jogger utility as well as the interaction of biker utility and total humans show minimal impact on the disturbance of any bird species. Nest failure was strongly influenced by both total humans and the utility on or off-trail option.

The utility experienced by different recreationist types within the simulated Fort Harrison State Park, was influenced by several predictor variables. Off-trail and utility guard were the most important variables across recreationist types. Having the off-trail and utility guard option on or off strongly influenced recreationist utility. In particular, hikers and birders were very sensitive to the off-trail option while bikers and joggers were influenced by utility guard option. The remaining predictor variables minimally influenced the effect size for all recreationist types. Total time recreationists spent in park was more strongly influenced by the number of simulated humans than any other variables (Table 2.8).

2.6 Discussion

Our study documented differences in bird disturbance rate, between SoDA and HaWAI models, however effect sizes were much larger for the number of simulated humans (Table 2.1). This is not surprising, as empirical studies show that increasing the number of humans has an effect on bird disturbance (Fernandez-Juricic et al., 2000). Studies have shown that as human recreation increased the frequency of the disturbance of wildlife increased (Bennett et al., 2013a, D'Acunto et al., 2018, Rodriguez-Prieto et al., 2014 but see Bennett et al., 2013b). Underlying this is the fact that increasing numbers of humans increases the frequency of encounters between birds and humans. The corresponding increase in disturbance of birds decreases their fitness (Boetsch et al., 2018). In many systems, the increasing cumulative disturbance of birds has a much stronger effect than does the type of human recreationist causing that disturbance (Botsch et al., 2018). Thus, the slight changes in the number of encounters between birds and humans associated with HaWAI's use of adaptive humans are inconsequential relative to the number of humans in the park increasing from 40 to 90. This illustrates that at their core, SoDA and HaWAI share a lot of common assumptions and model structures. The primary difference is HaWAI's ability to estimate the utility of human agents and change their behavior based upon that utility. To standardize our comparison of model types, in our first experiment we only implemented features of HaWAI that had parallels within SoDA. For example, because humans in SoDA could not move off-trail to pursue birds, we turned that capability off in our HaWAI runs. However, implementing such additional capabilities might have elucidated more differences between modeling approaches.

Given the difference in how SoDA and HaWAI emulate human activity, it is surprising that model type did not have a larger effect size. More specifically, during each time step SoDA generates virtual humans at random points along trails and has them move for a single time step before they disappear from the model. In contrast, HaWAI generates virtual humans at trail heads and simulates their movements across multiple time steps until they move along the trail return to the trail head and leave the park. This difference might cause more clusters in disturbance activity in HaWAI near trail heads. However, our comparison suggests the stochastic approach used in SoDA does not change disturbance as much as total humans which explains nearly 5 times more variation in disturbance.

Despite the subtle differences in the disturbance of wildlife associated with using HaWAI, the model offers insights not available from SoDA. Specifically, the behavior of humans within HaWAI emerges from their use of adaptive rules rather than imposed patterns. As a consequence, results from HaWAI provides insights into the quality and quantity of human experiences not available from SoDA. Thus, the fundamental advancement in HaWAI is allowing human utility to emerge from agent behavior rather than being imposed. The resulting inference could inform management of recreation at parks with multiple use mandates. For example, many green spaces may place an equal or greater emphasis upon the quality of human recreation than the conservation of wildlife. So simultaneous insights into each of these responses may be invaluable.

It is important to understand how the additional capabilities provided by HaWAI influence variation in the disturbance of birds. Thus, our second experiment simulated Fort Harrison State Park implementing the full range of HaWAI capabilities. This included a contrast of the utility on and off feature as well as the ability for virtual humans to go off-trail. The resulting relatively small effect size of the utility guard feature in this experiment was consistent with the small effect size for model type in our first experiment. This reinforces our previous interpretation that simulating human utility does not change bird disturbance as much as other factors. However, within results from our second experiment investigating the behavior of HaWAI on its own the difference between models within the off-trail option where humans were or were not allowed to leave the trail was influential in bird disturbance. This model result is supported by empirical studies that document increased disturbance of wildlife when recreationists leave trails (Taylor et al., 2003, Coppes et al., 2013, Neumann et al., 2010). For example, a study of nestlings of Black-crowned Night-Herons demonstrated significantly more negative responses when humans on trails moved in an inquisitive way including veering off-trails (Fernandez-Juricic et al., 2007). It is noteworthy that our results from scenarios when humans leave and don't leave trails, when all else is equal, are highly consistent with the aforementioned empirical studies. This convergence illustrates the value of parallel research using ABMs and empirical studies.

Within results from our second experiment the influence of utility of different recreationist types upon disturbance generally had a low effect size (see table 2.6). This is not surprising as the frequency of disturbance is more important to birds than the type of recreationist causing the disturbance (Blumstein et al., 2005). Recall that we parameterized the frequency of occurrence of each recreationist type in the park according to the results of the intercept survey from LCFU. These survey results suggest that birders and hikers should have the greatest impact on bird disturbance (Radulski, 2020). However, our results document that birders and hikers minimally influenced bird disturbance. In contrast, joggers were the most influential recreationist type in the HaWAI results. This likely occurs because joggers have more encounters with birds. That observation contradicts the fact that fewer joggers are simulated than other recreationist types. However, joggers are likely to stay in the park longer than other recreationists because their utility is diminished the least by encounters with other recreationists (Radulski, 2020). Interestingly, in related empirical work Lethlean et al., (2017), documented that joggers disturbed birds more than walkers. He states that birds have more intense responses to joggers at greater distances. These findings by Lethlean et al., (2017), suggest that recreationist types should have been a more important factor in our model results. This difference suggests that there is more complexity to relationships between recreationist type and bird disturbance thus framing future intercept surveys differently may provide more useful information.

Characteristics of individual bird species such as their relative abundance and sensitivity to human activity may also impact the levels of disturbance they experience when modeled with

HaWAI. Such factors can provide important insights when managing species in a park. When comparing the effect size for off-trail among our species, Carolina Chickadee and Downey Woodpecker both had high effect sizes and are common and widespread species, with a low sensitivity to disturbance. Although these two species are insensitive to disturbance, humans venturing off-trail will increase their proximity to these common and widespread birds thereby increasing disturbance rates. In contrast, Hooded Warblers are highly sensitive to disturbance and uncommon but they still exhibit a high effect size for off-trail. This contrast demonstrates the importance of considering all facets of a species characteristics when understanding how their level of disturbance responds to various factors. A similar example contrasts the effect size of total humans across the simulated species. In this case, Wood Thrush, Eastern Wood-Pewee and Kentucky Warbler are all common but declining species that experience an intermediate effect size from total humans. These patterns appear to be more a function of species rarity than sensitivity. In contrast the Carolina Chickadee is a common species with a robust population and Brown Creeper is an uncommon species with a stable population and they experience a high effect size from total humans. The above examples from our results illustrate the relative influence of various factors upon the levels of disturbance experienced by these species we simulated. Such mechanistic insight can be considered along with the conservation status of species to inform a prioritization of management activities.

HaWAI provides insights into the experience of recreationists within a park that are not available from disturbance models like SoDA. These insights can inform decision making by comparing model scenarios for all recreationist types. For example, based upon model parameters, we expected the utility of recreationist types to have high effect sizes for birders but our results differed showing that recreationists utility was most sensitive to on and off-trail and utility guard. Thus, when hikers go off the trail, they have an increased probability of encountering birds, contributing to this increased effect size. In contrast, when off-trail option is off, the concentration of all recreationists along the trails will increase the frequency of encounters with other recreationists thereby altering the hiker's utility and decreasing their time spent in the park. However, recreationists' experiences can be influenced by more than just encounters with birds and other recreationists. Factors like the location of encounters on trails and the recreationists' preference for specific areas of the park may also influence their utility. For example, a muddy or trash filled trail can reduce enjoyment of a park (Verlic et al., 2015). Ultimately, one of the values of HaWAI is its ability to identify distinctions in the emergent behavior of recreationist types. Such information can bring valuable insights informing park management to maximize recreationists experiences.

The distinguishing value of HaWAI is its ability to provide insights into the emergent human and wildlife responses to simulated management. HaWAI's capability to simulate realistic behaviors, like recreationists veering off-trails, enables users to compare scenarios and estimate their consequences. Using this tool, we were able to gain valuable insights from multiple bird species. Specifically, we considered the sensitivity of species to human disturbance as well as their relative rarity to assess the importance of each of those factors. Such comparisons are especially important when modeling a suite of wildlife species to inform park management.

In conclusion, we demonstrated the importance of considering many factors when deciding how to manage wildlife communities and recreationists within a park. Interestingly, the relative importance of different factors on the disturbance of birds differed between our model results and the responses recreationists provided to the intercept survey. This distinction emphasizes the importance the cumulative perspective offered by the use of an ABM. For example, other research has documented that many recreationists assume that bird watchers have the highest impact on bird disturbance (Weston et al., 2015). However, our model results differ from this assumption. Instead recreationists types that use the park more intensively had a stronger impact on the disturbance of birds. Another example of a deviation of our model results from conventional wisdom relates to the utility recreationists experience in the park. Contrary to the expectation that recreationist utility is strongly influenced by encounters with other recreationists in the park, our model results suggest utility is largely a function of how recreationists use the trail. The approach we developed and illustrated in this paper of simulating multiple adaptive agents can be expanded to different landscapes and scenarios to enhance the conservation of wildlife communities. This approach of simultaneously simulating interacting wildlife and humans will be relevant to the management of parks around the world.

Table 2.1 Parameters used in HaWAI submodels and their corresponding values

Parameter	**Value**	**Reference**
Simulation duration	21 days / 30,240 timesteps	Alex Cohen Pers. Com.
Periods of day (same periods for both weekdays and weekends)	Night (10 pm to 6 am), Early Morning (6 am to 9 am), Late Morning (9 am to 12 pm), Early Afternoon (12 pm to 3 pm), Late Afternoon (3 pm to 7 pm), Evening (7 pm to 10 pm)	Alex Cohen Pers. Com.
Multiplier for overall human density by period of day (can parameterize different values for weekday vs. weekend)	Night: 0, Early Morning: 0.15, Late Morning: 0.3, Early Afternoon: 0.5, Late Afternoon: 1, Evening: 0.3	Alex Cohen Pers. Com.
Probability of adding particular types of recreationists (can be unique for each of 12 periods of day/week)	[0.25 0.25 0.25 0.25] = equal chance of any recreationist being added	Alex Cohen Pers. Com.
Maximum number of humans	40, 60, 90	Alex Cohen Pers. Com.
Chance of adding human (per ts) if below maximum * time-of-day multiplier	0.5	Alex Cohen Pers. Com.
Default speed (biker/jogger/hiker/birder)	200 / 80 / 40 / 20 cells per min (1 cell = 2 meters)	Alex Cohen Pers. Com.
Speed when triggered to leave	200 / 80 / 40 / 40 cells per min	Alex Cohen Pers. Com.
Change in speed when passing (+ cells)	40 / 20 / 20 / 20 cells per min (commented out)	Alex Cohen Pers. Com.
Change in speed when being passed (- cells)	NA / 20 / 20 / 20 cells per min	Alex Cohen Pers. Com.
Initial time budgeted to stay in park: mean (biker/jogger/hiker/birder)	60 / 60 / 60 / 90 minutes	Alex Cohen Pers. Com.
Initial time budget to stay in park: standard dev	10 / 10 / 10 / 15 minutes	Alex Cohen Pers. Com.
Maximum time possible to stay in park	90 / 90 / 90 / 120 minutes	Alex Cohen Pers. Com.
Average timesteps taken to leave the park (based on running the model given numbers of various recreationists, time budgets, etc.)	4 / 12 / 27 / 32 minutes on regular trails 4 / 9 / 20 / 20 minutes with old trails as shortcuts	Alex Cohen Pers. Com.

Table 2.1 continued

Chance per human to cause disturbance when within bird FID/alert distances	0.018 (results in a comparable amount of disturbance as SODA-type humans and speeds model up dramatically)	Alex Cohen Pers. Com.
Interval to re-calculate utility	10 minutes	Alex Cohen Pers. Com.
Chance of entering at NW entrance vs. east	Equal chance	Alex Cohen Pers. Com.
Chance of exiting at point of entrance	1	Alex Cohen Pers. Com.
Bird detection radius mean (birders / hikers)	10 / 5 cells (1 cell = 2 meters)	Alex Cohen Pers. Com.
Bird detection radius standard deviation	2 / 1 cells	Alex Cohen Pers. Com.
Chance of detecting one bird if any are within bird detection radius	0.9 / 0.5	Alex Cohen Pers. Com.
Chance of detecting additional birds within detection radius if one has already been detected	0.5 / 0.2	Alex Cohen Pers. Com.
Chance to stop and watch detected birds: regular	0.5 / 0.25	Alex Cohen Pers. Com.
Chance to stop and watch detected birds: leaving	0.25 / 0	Alex Cohen Pers. Com.
If stopped watching a bird, chance to start moving again per mini-timestep (3 sec): regular	0.05 / 0.1	Alex Cohen Pers. Com.
If stopped watching a bird, chance to start moving again per mini-timestep (3 sec): leaving	0.2 / 0.3	Alex Cohen Pers. Com.
Chance of moving in a particular direction at trail intersection: normal	Equal chances at all intersections • Can’t leave simulation before triggered to leave • Bikers can’t go onto old trails	Alex Cohen Pers. Com.
Chance of moving in a particular direction at trail intersection: when leaving	Directed in a particular direction at every trail intersection based on their target exit	Alex Cohen Pers. Com.
Nests: energy threshold needed to remain successful every day (out of 166 max)	150	Alex Cohen Pers. Com.
Encounters counted as negative: bikers	Bikers, joggers, hikers, birders	Radulski et al., 2020, intercept survey Fort Harrison State Park, IN
Encounters counted as negative: joggers	Bikers, joggers, hikers, birders	Radulski et al., 2020, intercept survey Fort Harrison State Park, IN

Table 2.2 continued

Encounters counted as negative: hikers	Bikers, joggers	Radulski et al., 2020, intercept survey Fort Harrison State Park, IN
Encounters counted as negative: birders	Bikers, joggers	Radulski et al., 2020, intercept survey Fort Harrison State Park, IN
Distances at which guard (which prevents utility accumulation) is removed after negative encounters	7 cells if passed from behind 5 cells otherwise	Alex Cohen Pers. Com.
Weights for which trail segments are preferred by recreationists: 8 different trail segments	[1 1 1 1 1 1 1 1] = no preference for every recreationist type	Alex Cohen Pers. Com.

Table 2.2 Sensitivity to disturbance, common or uncommon status and habitat preference of 9 birds species in the Lawrence Creek Forest Unit of Fort Harrison State Park, IN. Information obtain for this table was made available from Rodriguez et al., 2014 and Audubon.org

Species	**Sensitivity to disturbance**	**Locally Common or Uncommon**	**Habitat preference**
Downy Woodpecker *Picoides pubescens*	Low	Common and widespread	Less mature stands
Eastern Wood-Pewee *Contopus virens*	Intermediate	Common with slight decline	Sparse understory and less mature stands
Acadian Flycatcher *Empidonax virescens*	Intermediate	Common	Mature stands with sparse understory
Carolina Chickadee *Poecile carolinensis*	Low	Common and widespread	No preference
Brown Creeper *Certhia americana*	Intermediate	Uncommon	Mature stands with sparse understory
Wood Thrush *Hylocichla mustelina*	Highly	Common with serious decline	Dense understory
Kentucky Warbler *Oporornis formosus*	Highly	Common with decline	Dense understory
Hooded Warbler *Wilsonia citrina*	Highly	Uncommon	Dense understory
Ovenbird *Seiurus aurocapilla*	Highly	Uncommon	Mature stands with sparse understory

Table 2.3 List of response variables to be measured and definitions

Response Variables	**Definition**
Total disturbance count birds	Number of times all species of birds are alert and flushed by each recreationist
Total Number of Nests failed for all bird species	Number of times nests fail to successfully fledge nestlings
Number of recreationists leaving early or late	Total number each recreationist type exiting park before simulation ends or extending their stay
Average utility on exit for each recreationist	The average of the satisfaction each human recreationist of a particular type for all of the time steps they spent in the park

Table 2.4 List of predictor variables, their definitions and their levels

Predictor Variables	Definition	Levels
Total humans	Number of recreationist type in each simulation.	40, 60, 90
Utility guard	A recreationists' utility is / is not a function of encounters with other recreationists.	On, Off
Nests fail	Nests ability to fail function	On, Off
Off-trail	Ability for human recreationists to veer off-trail	On, Off

Table 2.5 Eta squared values for SoDA vs HaWAI models showing the effect size each independent variable has on the disturbance of 9 bird species in Fort Harrison State Park, IN. Corresponding confidence intervals are at a 95% level.

Species Disturbed	**Model Type**	**Total humans**
Ovenbird	0.0022 (0.00, 0.05)	0.0100 (0.00, 0.08)
Hooded Warbler	0.0059 (0.00, 0.06)	0.0800 (0.01, 0.19)
Carolina Chickadee	0.0092 (0.00, 0.07)	0.3000 (0.17, 0.42)
Brown Creeper	0.0054 (0.00, 0.06)	0.2200 (0.10, 0.34)
Downy Woodpecker	0.0027 (0.00, 0.05)	0.2100 (0.10, 0.34)
Acadian Flycatcher	0.0060 (0.00, 0.06)	0.0001 (0.00, 0.02)
Kentucky Warbler	0.0300 (0.00, 0.12)	0.0077 (0.00, 0.07)
Eastern Wood- Pewee	0.0200 (0.00, 0.10)	0.0052 (0.00, 0.06)
Wood Thrush	0.0087 (0.00, 0.07)	0.0200 (0.00, 0.09)
All species	0.0500 (0.00, 0.14)	0.2400 (0.12, 0.36)
Nests failed	0.0200 (0.00, 0.10)	0.5300 (0.41, 0.62)

Table 2.6 Eta squared values showing the effect size each independent variable has on the disturbance of 9 bird species in Fort Harrison State Park, IN simulated using the adaptive HaWAI model. Corresponding confidence intervals are at a 95% level.

Species Disturbance	**Off-trail**	**Utility guard**	**Total humans**	**Utility biker**	**Utility birder**	**Utility hiker**	**Utility jogger**	**Biker : jogger**	**Total humans : biker**	**Total humans : jogger**
Ovenbird	0.0800 (0.00, 0.26)	0.0018 (0.00, 0.09)	0.0074 (0.00, 0.08)	0.0100 (0.00, 0.14)	0.0400 (0.00, 0.19)	0.0100 (0.00, 0.13)	0.0013 (0.00, 0.09)	0.0100 (0.00, 0.14)	0.0400 (0.00, 0.17)	0.0700 (0.00, 0.22)
Hooded Warbler	0.1500 (0.02, 0.35)	0.0001 (0.00, 0.04)	0.0800 (0.00, 0.24)	0.0100 (0.00, 0.15)	0.0086 (0.00, 0.13)	0.0500 (0.00, 0.22)	0.0600 (0.00, 0.23)	0.0010 (0.00, 0.08)	0.0013 (0.00, 0.01)	0.0400 (0.00, 0.17)
Carolina Chickadee	0.3400 (0.13, 0.51)	0.0100 (0.00, 0.14)	0.1400 (0.00, 0.32)	0.0040 (0.00, 0.11)	0.0029 (0.00, 0.10)	0.0012 (0.00, 0.08)	0.0079 (0.00, 0.12)	0.0015 (0.00, 0.09)	0.0200 (0.00, 0.14)	0.0200 (0.00, 0.12)
Brown Creeper	0.0500 (0.00, 0.22)	0.1200 (0.00, 0.30)	0.1400 (0.00, 0.32)	0.0063 (0.00, 0.12)	0.0200 (0.00, 0.15)	0.0089 (0.00, 0.13)	0.0100 (0.00, 0.14)	0.0002 (0.00, 0.05)	0.0005 (0.00, 0.00)	0.0100 (0.00, 0.10)
Downy Woodpecker	0.1900 (0.03, 0.38)	0.0006 (0.00, 0.06)	0.0600 (0.00, 0.21)	0.0049 (0.00, 0.11)	0.0400 (0.00, 0.20)	0.0015 (0.00, 0.09)	0.0100 (0.00, 0.13)	0.0400 (0.00, 0.20)	0.0300 (0.00, 0.15)	0.0012 (0.00, 0.01)
Acadian Flycatcher	0.1000 (0.00, 0.28)	0.0100 (0.00, 0.14)	0.0200 (0.00, 0.13)	0.0005 (0.00, 0.06)	0.0047 (0.00, 0.11)	0.0021 (0.00, 0.09)	0.0300 (0.00, 0.18)	0.0006 (0.00, 0.07)	0.0300 (0.00, 0.15)	0.0200 (0.00, 0.11)
Kentucky Warbler	0.0034 (0.00, 0.10)	0.0100 (0.00, 0.13)	0.0500 (0.00, 0.18)	0.0021 (0.00, 0.09)	0.0044 (0.00, 0.11)	0.0200 (0.00, 0.15)	0.0700 (0.00, 0.25)	0.0200 (0.00, 0.15)	0.0500 (0.00, 0.20)	0.0300 (0.00, 0.14)
East Wood Pewee	0.0045 (0.00, 0.11)	0.0048 (0.00, 0.11)	0.0500 (0.00, 0.20)	0.0300 (0.00, 0.17)	0.0002 (0.00, 0.04)	0.0032 (0.00, 0.10)	0.1000 (0.00, 0.28)	0.0049 (0.00, 0.11)	0.0200 (0.00, 0.13)	0.0400 (0.00, 0.18)
Wood Thrush	0.0300 (0.00, 0.17)	0.0015 (0.00, 0.09)	0.0500 (0.00, 0.19)	0.0083 (0.00, 0.13)	0.1000 (0.00, 0.28)	0.0000 (0.00, 0.02)	0.0800 (0.00, 0.26)	0.0092 (0.00, 0.13)	0.0100 (0.00, 0.10)	0.0500 (0.00, 0.20)
All species	0.0800 (0.00, 0.25)	0.0067 (0.00, 0.12)	0.2100 (0.02, 0.39)	0.0004 (0.00, 0.06)	0.0700 (0.00, 0.25)	0.0019 (0.00, 0.09)	0.1800 (0.03, 0.37)	0.0018 (0.00, 0.09)	0.0100 (0.00, 0.10)	0.0013 (0.00, 0.01)

Table 2.7 Eta squared values showing the effect size each independent variable has on recreationist utility type in Fort Harrison State Park, IN simulated using the adaptive HaWAI model. Corresponding confidence intervals are at a 95% level.

Recreationist type	Off-trail	Utility guard	Total humans	Utility birder	Utility biker	Utility jogger	Utility hiker	Off tail: birder
Birder	0.0600 (0.00, 0.19)	0.0400 (0.00, 0.16)	0.0100 (0.00, 0.07)	n/a	0.0041 (0.00, 0.18)	0.0500 (0.00, 0.18)	0.0027 (0.00, 0.07)	n/a
Biker	0.0200 (0.00, 0.13)	0.0700 (0.00, 0.21)	0.0200 (0.00, 0.10)	0.0048 (0.00, 0.08)	n/a	0.0001 (0.00, 0.00)	0.0002 (0.00, 0.02)	0.0052 (0.00, 0.08)
Jogger	0.0400 (0.00, 0.17)	0.0600 (0.00, 0.20)	0.0200 (0.00, 0.09)	0.0500 (0.00, 0.18)	0.0001 (0.00, 0.00)	n/a	0.0003 (0.00, 0.07)	0.0007 (0.00, 0.04)
Hiker	0.1100 (0.01, 0.25)	0.0024 (0.00, 0.07)	0.0200 (0.00, 0.09)	0.0033 (0.00, 0.07)	0.0002 (0.00, 0.00)	0.0003 (0.00, 0.00)	n/a	0.0300 (0.00, 0.15)

Recreationist type	Off-trail: biker	Off-trail: jogger	Off-trail: hiker
Birder	0.0027 (0.00, 0.07)	0.0018 (0.00, 0.06)	0.0300 (0.00, 0.14)
Biker	n/a	0.0300 (0.00, 0.15)	0.0100 (0.00, 0.10)
Jogger	0.0100 (0.00, 0.11)	n/a	0.0030 (0.00, 0.07)
Hiker	0.0082 (0.00, 0.02)	0.0029 (0.00, 0.07)	n/a

Table 2.8 Eta squared values showing the effect size each independent variable has on all recreationists leaving early or late in Fort Harrison State Park, IN simulated using the adaptive HaWAI model. Corresponding confidence intervals are at a 95% level.

All Recreationists	Off-trail	Utility guard	Total humans	Utility birder	Utility biker	Utility jogger	Utility hiker	Biker: Birder	Birder: Jogger	Birder: Hiker
Left early	0.0001 (0.00, 0.00)	0.0001 (0.00, 0.00)	1.0000 (0.99, 1.00)	0.0000 (0.00, 0.00)	0.0000 (0.00, 0.00)	0.0001 (0.00, 0.00)	0.0000 (0.00, 0.00)	0.0000 (0.00, 0.00)	0.0001 (0.00, 0.00)	0.0001 (0.00, 0.00)
Stayed late	0.0010 (0.00, 0.05)	0.0001 (0.00, 0.00)	0.9800 (0.97, 0.98)	0.0000 (0.00, 0.00)	0.0000 (0.00, 0.00)	0.0001 (0.00, 0.00)	0.0004 (0.00, 0.03)	0.0000 (0.00, 0.00)	0.0001 (0.00, 0.00)	0.0001 (0.00, 0.00)

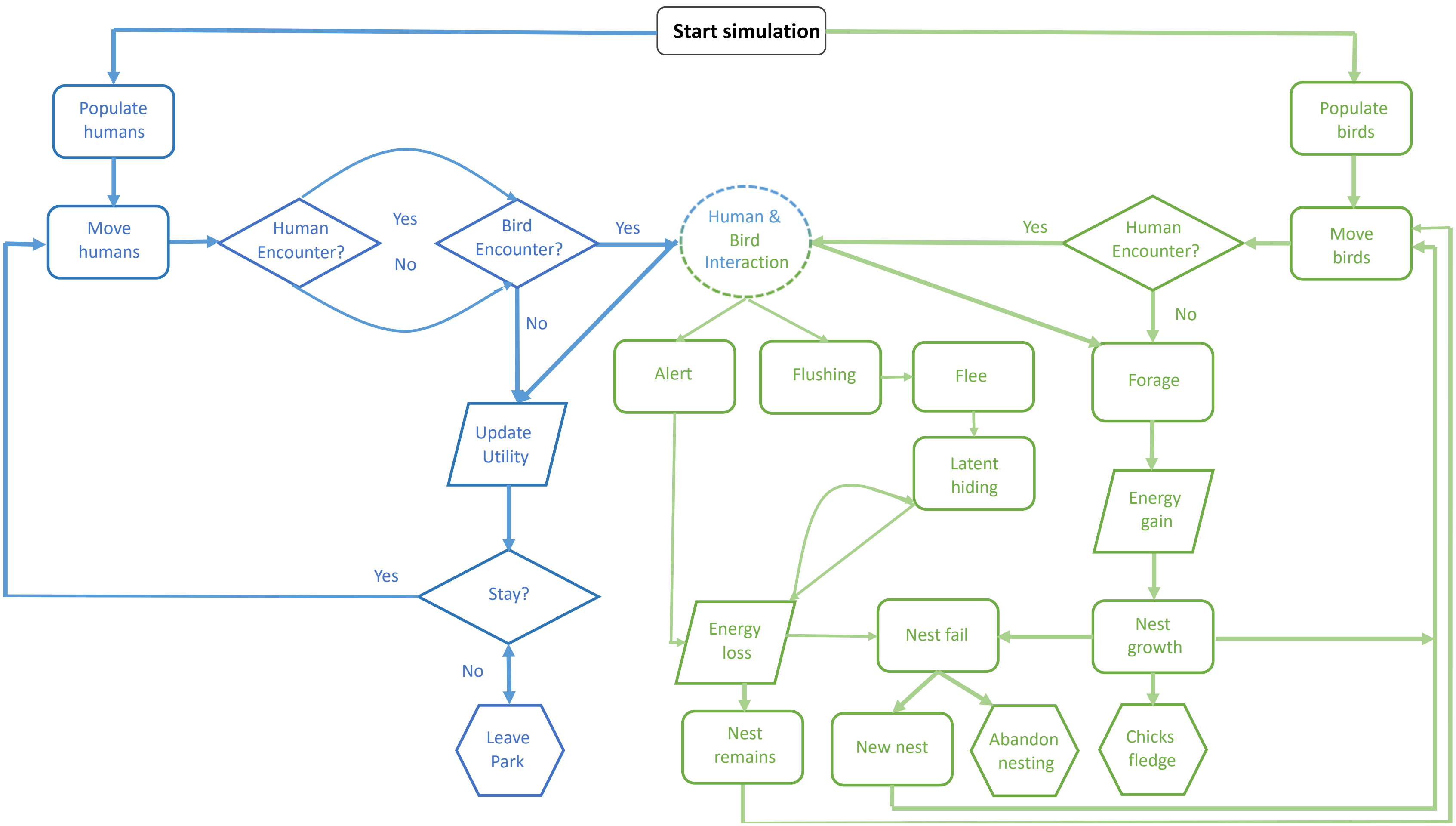

Figure 2.1 HaWAI framework flowchart demonstrating the synchronized simulation process of human recreationists (blue) and bird agent behavior (green). Direction of arrows indicate the flow of decision making and behavior or action taken while making one complete simulation run. Humans move through trail interacting with other humans or birds accumulating utility with each timestep eventually deciding to leave the park or stay. Birds interact with humans becoming alert or flushing while losing energy resulting in nest failure, abandonment or persistence. If no interaction with humans occur, birds forage and gain energy creating nest growth and fledglings.

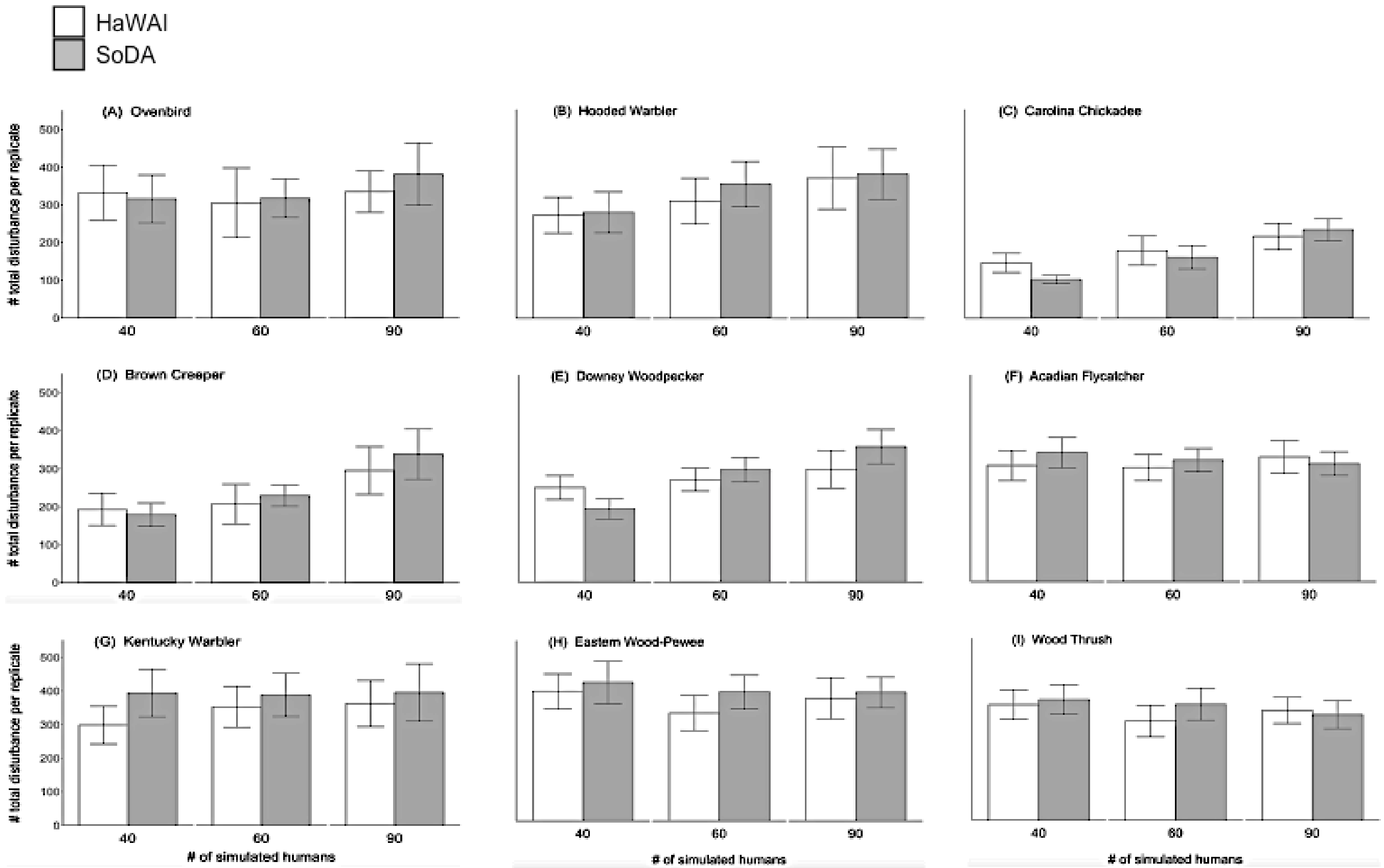

Figure 2.2 A comparison of the number of disturbances between the HaWAI and SoDA models at levels of humans 40, 60 and 90 in each model replicate for individual species panel (A) Ovenbird, (B) Hooded Warbler, (C) Carolina Chickadee, (D) Brown Creeper, (E) Downy Woodpecker, (F) Acadian Flycatcher, (G) Kentucky Warbler, (H) Eastern Wood-Pee, (I) Wood Thrush.

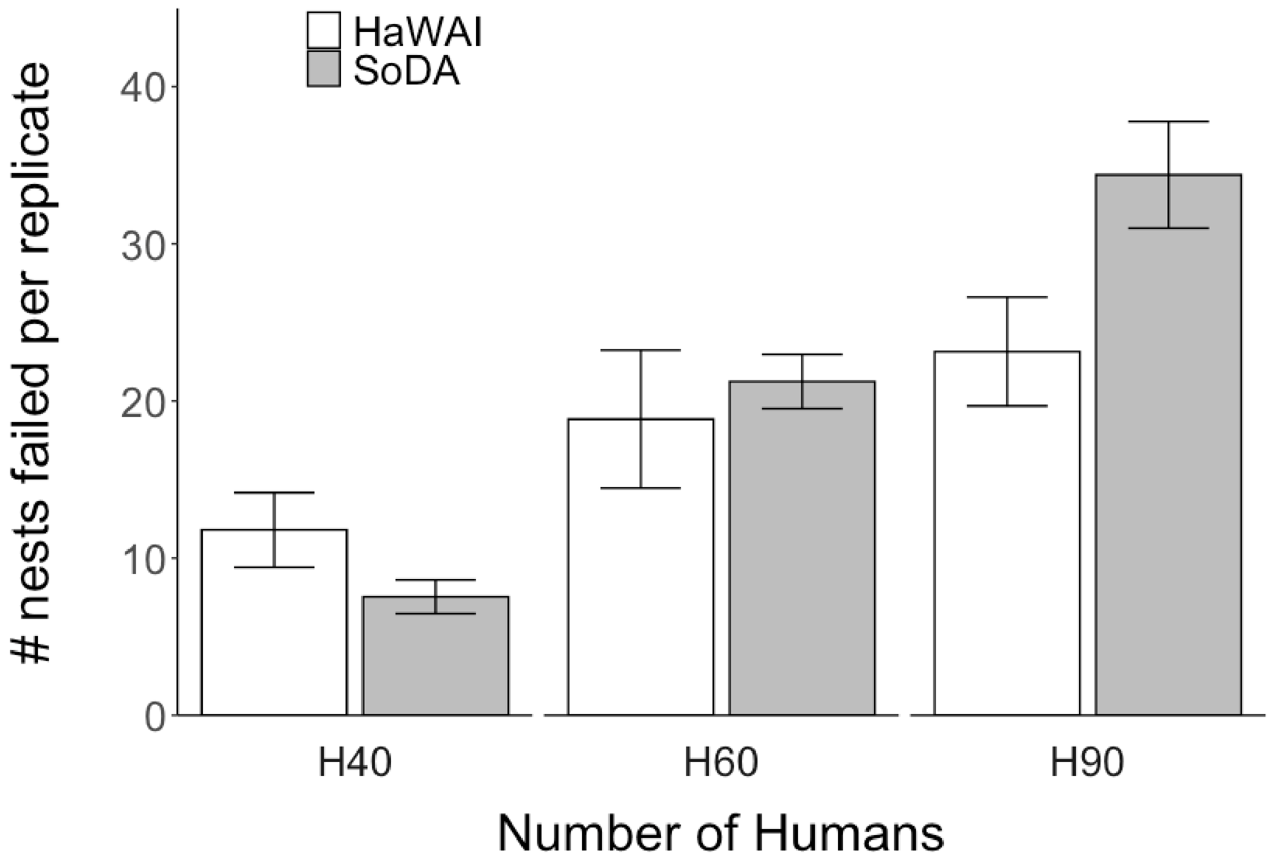

Figure 2.3 A comparison of the number of nests failing per replicate model run between the HaWAI and SoDA models summed across all bird species at levels of humans 40, 60 and 90.

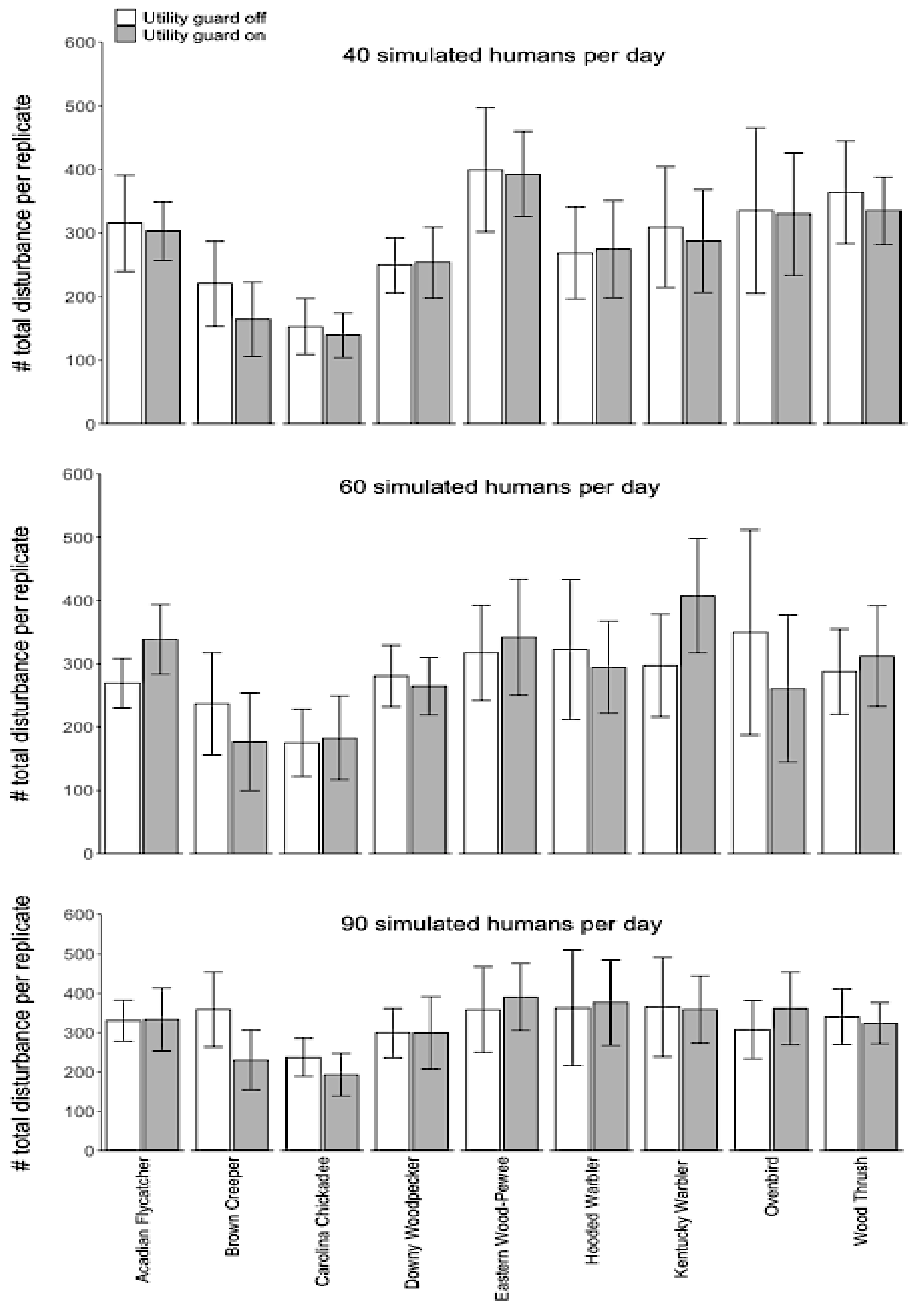

Figure 2.4 Comparing the total number of disturbances when utility guard is on or off. When utility guard is on, recreationists will not accumulate utility when experiencing a negative encounter. When utility guard is off recreationists will accumulate utility. This was simulated using the adaptive HaWAI model at levels of 40, 60 and 90 humans in each model replicate.

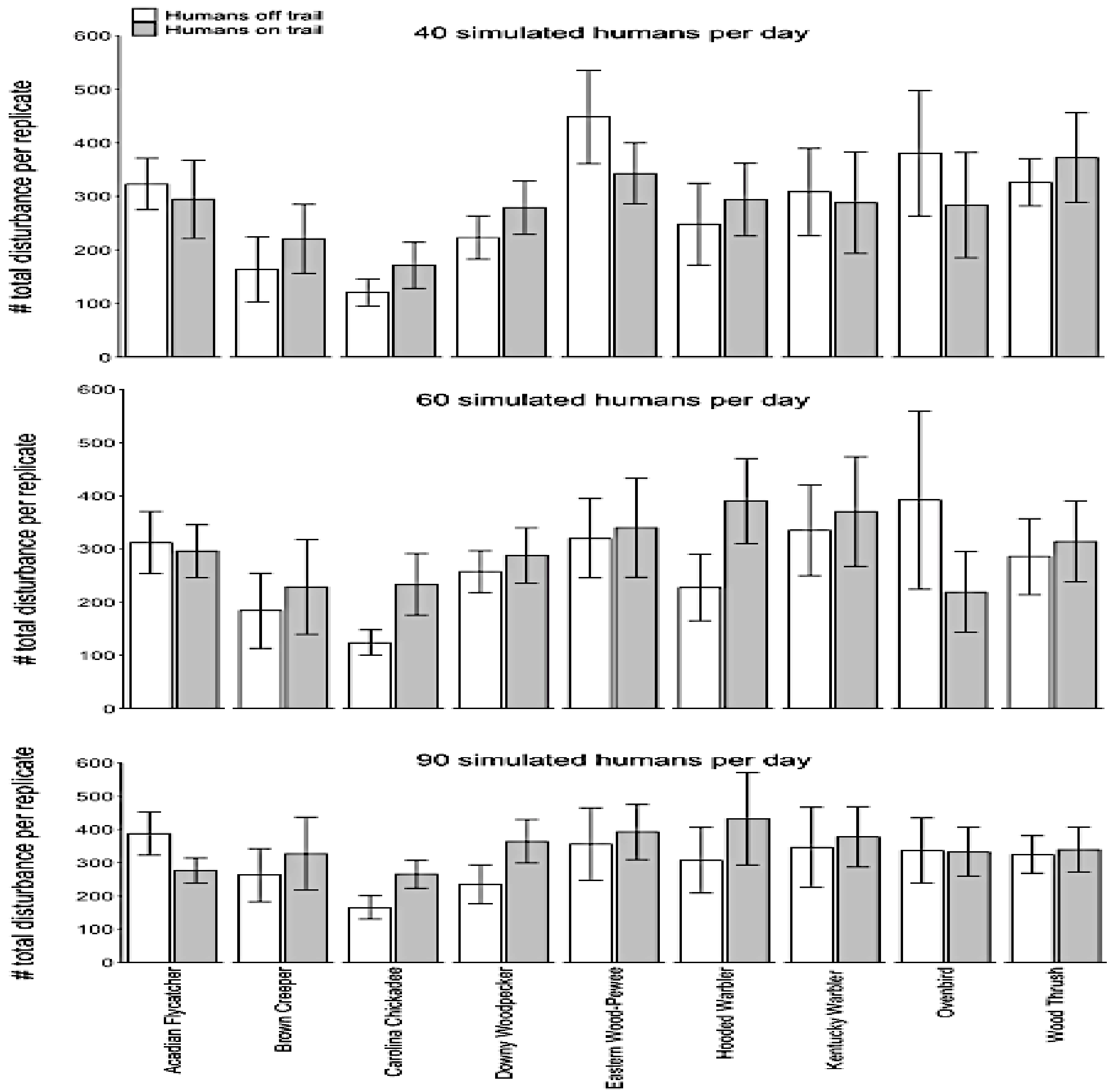

Figure 2.5 Comparing the total number of disturbances of birds when humans are off and on trail for all bird species when simulating 40, 60 and 90 humans in the park using the adaptive HaWAI model.

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APPENDIX A. RECREATIONISTS PARAMETERS

The following tables contain empirical values that were measured from raw data collected through the intercept survey at Fort Harrison State Park, IN. The values were calculated according to the questions asked for each recreationist type. These values were used to generate human recreationist behavior rules in the HaWAI model.

Table A.1 The frequency of recreationists on trail by time of day

		Frequency on Trail at Interval			
	Time	Biker	Hiker	Birder	Jogger
night	10pm - 6am	0	0	0	0
early morning	6am - 9am	2	1	4	0
late morning	9am - 12pm	6	12	15	9
early afternoon	12pm - 3pm	13	27	6	5
late afternoon	3pm - 7pm	14	26	3	5
evening	7pm - 10pm	0	4	2	4

Table A.2 The probability of recreationists on trail by time of day values below were generated from the frequency data in table A.1

		Probability on Trail			
	Time	Biker	Hiker	Birder	Jogger
night	10pm - 6am	0	0	0	0
early morning	6am - 9am	0.29	0.14	0.57	0
late morning	9am - 12pm	0.14	0.29	0.36	0.21
early afternoon	12pm - 3pm	0.25	0.53	0.12	0.1
late afternoon	3pm - 7pm	0.29	0.54	0.06	0.11
evening	7pm - 10pm	0	0.4	0.2	0.4

Table A.3 The average amount of time each type of recreationist spends on trail

	Time on Trail			
	Biker	Birder	Hiker	Jogger
Average	1.175	1.587	1.464	1.117
STDEV	0.717	0.962	0.632	0.603

Table A.4 The frequency of responses given by Bikers for levels of enjoyment when encountering other recreationists on trail. The proportions for each category in each column were generated by dividing the cell of each category by the sum of entire column. A score of 0,1 or 2 was then given to each category (moderately and minimally were considered as one category), where 0 not annoyed, 1 annoyed and 2 extremely annoyed. These scores were part of the utility function human behavior rule for each recreationist type in the HaWAI model.

	Bikers			
	joggers_enj	hikers_enj	birders_enj	bicyclists_enj
Greatly reduce my enjoyment	0	2	0	1
Moderately reduce my enjoyment	1	3	0	2
Minimally reduce my enjoyment	4	10	1	6
Does not reduce my enjoyment at all	31	19	25	23

Table A.5 The frequency of responses given by Hikers for levels of enjoyment when encountering other recreationists on trail. The proportions for each category in each column were generated by dividing the cell of each category by the sum of entire column. A score of 0,1 or 2 was then given to each category (moderately and minimally were considered as one category), where 0 not annoyed, 1 annoyed and 2 extremely annoyed. These scores were part of the utility function human behavior rule for each recreationist type in the HaWAI model.

	Hikers			
	joggers_enj	hikers_enj	birders_enj	bicyclists_enj
Greatly reduce my enjoyment	0	0	0	4
Moderately reduce my enjoyment	1	3	1	15
Minimally reduce my enjoyment	18	12	3	16
Does not reduce my enjoyment at all	48	39	20	29

Table A.6 The frequency of responses given by Joggers for levels of enjoyment when encountering other recreationists on trail. The proportions for each category in each column were generated by dividing the cell of each category by the sum of entire column. A score of 0,1 or 2 was then given to each category (moderately and minimally were considered as one category), where 0 not annoyed, 1 annoyed and 2 extremely annoyed. These scores were part of the utility function human behavior rule for each recreationist type in the HaWAI model.

	Jogger			
	joggers_enj	hikers_enj	birders_enj	bicyclists_enj
Greatly reduce my enjoyment	0	0	0	1
Moderately reduce my enjoyment	0	0	0	3
Minimally reduce my enjoyment	2	2	0	5
Does not reduce my enjoyment at all	20	21	12	11

Table A.7 The frequency of responses given by Birders for levels of enjoyment when encountering other recreationists on trail. The proportions for each category in each column were generated by dividing the cell of each category by the sum of entire column. A score of 0,1 or 2 was then given to each category (moderately and minimally were considered as one category), where 0 not annoyed, 1 annoyed and 2 extremely annoyed. These scores were part of the utility function human behavior rule for each recreationist type in the HaWAI model.

	Birder			
	joggers_enj	hikers_enj	birders_enj	bicyclists_enj
Greatly reduce my enjoyment	0	0	0	12
Moderately reduce my enjoyment	5	1	0	2
Minimally reduce my enjoyment	14	12	3	6
Does not reduce my enjoyment at all	10	16	25	3

Table A.8 Bikers respond yes or no if their enjoyment level increases when encountering the following scenarios. To find the proportion of enjoyment for each category, the probability of the "yes" response was calculated by dividing the cell of each category by the sum of the entire column. A score was assigned to each recreationist, 1 (highest) through 4 (lowest), based on the overall probabilities derived. These scores were part of the utility function human recreationist behavior rule for each recreationist type in the HaWAI model.

	Biker	
	Yes	No
I can hear birds	29	6
I can see birds	22	13
I can encounter wildlife other than birds	31	4
I can hear a rare bird	12	23
I can see a rare bird	10	25
I see very few people on the trails	16	19
I encounter acquaintances on the trail	25	10

Table A.9 Hikers respond yes or no if their enjoyment level increases when encountering the following scenarios. To find the proportion of enjoyment for each category, the probability of the "yes" response was calculated by dividing the cell of each category by the sum of the entire column. A score was assigned to each recreationist, 1 (highest) through 4 (lowest), based on the overall probabilities derived. These scores were part of the utility function human recreationist behavior rule for each recreationist type in the HaWAI model.

	Hiker	
	Yes	No
I can hear birds	60	8
I can see birds	53	15
I can encounter wildlife other than birds	51	17
I can hear a rare bird	24	44
I can see a rare bird	23	45
I see very few people on the trails	27	41
I encounter acquaintances on the trail	38	30

Table A.10 Joggers respond yes or no if their enjoyment level increases when encountering the following scenarios. To find the proportion of enjoyment for each category, the probability of the “yes” response was calculated by dividing the cell of each category by the sum of the entire column. A score was assigned to each recreationist, 1 (highest) through 4 (lowest), based on the overall probabilities derived. These scores were part of the utility function human recreationist behavior rule for each recreationist type in the HaWAI model.

	Jogger	
	Yes	No
I can hear birds	19	3
I can see birds	16	6
I can encounter wildlife other than birds	18	4
I can hear a rare bird	10	12
I can see a rare bird	10	12
I see very few people on the trails	4	18
I encounter acquaintances on the trail	14	8

Table A.11 Birders respond yes or no if their enjoyment level increases when encountering the following scenarios. To find the proportion of enjoyment for each category, the probability of the “yes” response was calculated by dividing the cell of each category by the sum of the entire column. A score was assigned to each recreationist, 1 (highest) through 4 (lowest), based on the overall probabilities derived. These scores were part of the utility function human recreationist behavior rule for each recreationist type in the HaWAI model.

	Birder	
	Yes	No
I can hear birds	27	1
I can see birds	28	0
I can encounter wildlife other than birds	17	11
I can hear a rare bird	12	16
I can see a rare bird	17	11
I see very few people on the trails	13	15
I encounter acquaintances on the trail	4	24

Table A.12 The frequency of a biker to stop and observe a common or rare bird. To find how often a biker would stop, the proportion of each category was calculated. The higher the probability, the higher the chance of stopping to watch a bird. These values were used for the stop and watch a bird rule in the HaWAI model.

	Biker	
	Common	Rare
Not likely at all	0	1
Somewhat likely	1	1
Very likely	0	2
Extremely likely	5	2

Table A.13 The frequency of a hiker to stop and observe a common or rare bird. To find how often a hiker would stop, the proportion of each category was calculated. The higher the probability, the higher the chance of stopping to watch a bird. These values were used for the stop and watch a bird rule in the HaWAI model.

	Hiker	
	Common	Rare
Not likely at all	1	11
Somewhat likely	3	7
Very likely	10	5
Extremely likely	10	1

Table A.14 The frequency of a jogger to stop and observe a common or rare bird. To find how often a jogger would stop, the proportion of each category was calculated. The higher the probability, the higher the chance of stopping to watch a bird. These values were used for the stop and watch a bird rule in the HaWAI model.

	Jogger	
	Common	Rare
Not likely at all	0	1
Somewhat likely	0	2
Very likely	1	3
Extremely likely	6	1

Table A.15 The frequency of a birder to stop and observe a common or rare bird. To find how often a birder would stop, the proportion of each category was calculated. The higher the probability, the higher the chance of stopping to watch a bird. These values were used for the stop and watch a bird rule in the HaWAI model.

	Birder	
	Common	Rare
Not likely at all	2	19
Somewhat likely	8	6
Very likely	15	1
Extremely likely	0	0

Table A.16 Comparison of different strategies for modeling human recreationists. SoDA-type humans reflect how humans were modeled in Rodríguez-Prieto et al. 2014. Adaptive-type humans have a variety of complexities.

Human Traits	**SODA**	**Adaptive**
Cause disturbance	X	X
Variation by time of day	X	X
Variation by type of recreationist (4 types)		X
Move along trails continuously		X
Duration of stay based on time budget		X
Can change duration of stay based on experience		X
Bird-related behavior: keep bird list, watch birds, etc.		X
Can move off trail to watch birds		X
Track encounters with other humans		X
Variable speed when passing/passed		X
Calculate utility at regular intervals		X

APPENDIX B. MODEL CODE

```
; Created by Alex Cohen & Soraida Garcia
; Date of creation: 1/12/2015
; Version 08/09 last modified: 8/17/2021 by Soraida Garcia
;
; Use this space to note any changes to code
; See version 08 for complete log of changes to this point
;
; Note that a single "patch" in this environment equals a 2x2 m extent in the real world
; Issues: For humans encountering other humans, around 10% of encounters are not recorded due to passing one cell away rather than through same cell (only way to fix this would be to take away all patches where this is possible)
;
;;;;;;;;;;;;;;;;;;;;;;; Represents transitions between major sections of code (globals, setup, go)
;###################### Represents delineation between major components of "go" (check-time-of-day, manage-humans, manage-birds)
;********************** Within "manage-humans", breaks down groupings of subprocedures
;^^^ on occasion within longer sections of procedures

;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;
;List of user-defined parameters associated with the simulated world and its inhabitants
extensions [gis] ;allows input of raster map
;globals are variables that are most easily accessible/changeable, generally simulation-level rather than agent characteristics
globals [Fort-Harrison time-until-rest time-until-forage foraging day time-of-day period-of-day human-timesteps nests-failed probabilities
  num-bikers num-hikers num-birders num-joggers cumul-biker-util cumul-hiker-util cumul-birder-util cumul-jogger-util avg-leaving-time num-left total-leaving-time
  bikers-left-early hikers-left-early birders-left-early joggers-left-early bikers-stayed-extra hikers-stayed-extra birders-stayed-extra joggers-stayed-extra calc-utility-interval]
patches-own [habitat trail-type] ;characteristics of patches
breed [birds bird] ;bird agents
breed [nests nest]
```

```
breed [humans human] ;human agents
;all the bird variables
birds-own [species rarity nesthab nestloc behavior energy curr-patch threat-patch threat-agent alert-count flush-count disturb-count FID-open alert-dist-open flush-dist-moved-open
  FID-cover alert-dist-cover flush-dist-moved-cover dist-by-biker dist-by-hiker dist-by-birder dist-by-jogger nest-attempt
  nesthab-prob-1 nesthab-prob-2 nesthab-prob-3 nesthab-prob-4 nesthab-prob-5] ;nesthab-probs are probabilities of nesting in the different habitat types, see setup-birds, create-a-bird, etc. these are saved so birds can renest
;all the human variables
humans-own [rec-type entry-point time-budget leaving-time orig-time-budget max-time-budget leaving speed dist-moved minutes-present bird-list num-birds-seen num-species-seen rate-birds-seen watching-bird? bird-agentset
  last-bird-enc-time birds-detected bird-detect-radius singlebird-prob-detect multibird-prob-detect patch-left heading-left
  last-encounter-agentset encountering last-encounter-time guarded guarded-against hiker-encounters biker-encounters jogger-encounters birder-encounters
  hiker-enc-behind biker-enc-behind jogger-enc-behind birder-enc-behind trail-type-cell-list beta-substitution overall-utility trail-utility bird-utility bad-ts bad-ts-threshold] ;encounter-neg-utility
;nest variables
nests-own [energy species associated-adult days-present]
;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;

;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;
;Procedures associated with setting up the model, all called by clicking the "setup" button in the interface

to setup ;reset NetLogo stuff, resize world to dimensions of LCU, display map and set up birds
  ca
  reset-ticks
  resize-world 0 567 0 463
  display-raster
  setup-birds
  setup-globals
end

to display-raster ;assign raster cell values to NetLogo patches through GIS extension
  ifelse old-trails-included?
```

```
  [set Fort-Harrison gis:load-dataset "C:/Desktop/PurdueUniversity/Zollner_Lab/lcu_rasterwitholdtrails.asc"] ;this map includes old trail A military trails
  [set Fort-Harrison gis:load-dataset "C:/Desktop/PurdueUniversity/Zollner_Lab/lcu_raster.asc"] ;this map shows the current set of trails in LCU
  gis:apply-raster Fort-Harrison habitat
  ; does not read in completely correctly so fix problem patches
  ;additionally, change some patches to/from trail to aid movement at intersections
    ask patch 519 252 [set habitat 3]
    ask patch 515 251 [set habitat 1]
    ask patch 516 252 [set habitat 20]
    ask patch 22 252 [set habitat 4]
    ask patch 23 252 [set habitat 4]
    ask patch 24 252 [set habitat 4]
    ask patch 25 252 [set habitat 4]
    ask patch 28 193 [set habitat 1]
    ask patch 29 195 [set habitat 50]
    ask patch 27 194 [set habitat 50]
    ask patch 127 380 [set habitat 4]
    ask patch 126 382 [set habitat 40]
    ask patch 128 381 [set habitat 40]
    ask patch 91 72 [set habitat 50]
    ask patch 94 74 [set habitat 50]
    ask patch 418 155 [set habitat 47]
  ;display patches based on habitat type (value of raster) and assign attributes
  ask patches [
    if habitat = 1 [set habitat "trail" set pcolor brown set trail-type "South"]
    if habitat = 2 [set habitat "trail" set pcolor brown set trail-type "North"]
    if habitat = 3 [set habitat "trail" set pcolor brown set trail-type "East Access"]
    if habitat = 4 [set habitat "trail" set pcolor brown set trail-type "Camp Glenn"]
    if habitat = 5 [set habitat "trail" set pcolor 52 set trail-type "Old Central"]
    if habitat = 6 [set habitat "trail" set pcolor 52 set trail-type "Old East"]
    if habitat = 7 [set habitat "trail" set pcolor 52 set trail-type "Old West"]
    if habitat = 8 [set habitat "trail" set pcolor 52 set trail-type "Old South"]
```

```
    if habitat = 10 [set habitat "native_relict" set pcolor 57]
    if habitat = 20 [set habitat "open_relict" set pcolor 6]
    if habitat = 30 [set habitat "native_young" set pcolor 93]
    if habitat = 40 [set habitat "honey_young" set pcolor 87]
    if habitat = 50 [set habitat "open_young" set pcolor 47]
    if habitat = 60 [set habitat "honey_relict" set pcolor 51]
  ;if you want to visualize disturbance, this overwrites previous color assignment and just makes patches black (except for trails)
    if Visualize-Disturbance and habitat != "trail" [set pcolor 10]]
end

to setup-birds ; create birds of each species, set disturbance parameters, nest locations based on probabilities of nesting in certain habitat types, etc.
  create-a-bird 7 "Ovenbird" 1 white 9 15 12.5 7 11.5 10 0 0.00001 0.00002 0.00003 0.8 ;if no chance to nest in habitat type, I just added 0.00001 to last value
  create-a-bird 8 "Hooded Warbler" 0.875 red 4.5 8.5 7.5 3 6 4 0.15 0.55 0.625 0.62501 0.875
  create-a-bird 16 "Carolina Chickadee" 0.4375 orange 2.5 4.5 7.5 2 4 5 0.0875 0.3625 0.36251 0.375 0.6875
  create-a-bird 8 "Brown Creeper" 0.875 turquoise 3.5 6 7.5 3 5 5 0 0.00001 0.025 0.02501 0.75
  create-a-bird 14 "Downy Woodpecker" 0.5 blue 4 6.5 7.5 3.5 5.5 6 0.086 0.443 0.44301 0.457 0.757
  create-a-bird 21 "Acadian Flycatcher" 0.333 violet 5.5 9 7.5 4.5 7.5 5 0.038 0.048 0.105 0.10501 0.771
  create-a-bird 7 "Kentucky Warbler" 1 magenta 6 10 7.5 4.5 7.5 6 0.229 0.571 0.714 0.71401 0.886
  create-a-bird 11 "Eastern Wood Pewee" 0.636 pink 6 10 7.5 5 8.5 6 0.018 0.164 0.182 0.18201 0.436
  ;Wood Pewee nest-calc (last 5 values) example: 1.8% chance to nest in honey_relict, 14.6% honey_young, 1.8% native_relict, 0% native_young, 25.4% open_relict, 56.4% open_young
  ;just accumulated probabilities to save code
  create-a-bird 15 "Wood Thrush" 0.467 lime 7.5 11 12.5 5.5 8 8 0.067 0.48 0.573 0.6 0.893
  create-nests 107 [set shape "dot" set size 3 move-to one-of patches with [count birds-here = 1 and count nests-here = 0] set color [color] of one-of birds-here
   set associated-adult one-of birds-here set species [species] of one-of birds-here set energy 0]
end

;parameters following each species corresponding with the following procedure inputs
to create-a-bird [number species-name rarity-value species-color FIDopen alertdistopen flushdistmovedopen FIDcover alertdistcover flushdistmovedcover
```

```
    calc-1 calc-2 calc-3 calc-4 calc-5]
   create-birds number [set shape "bird" set color species-color set size 8 set energy 10 set species species-name set rarity rarity-value
     set FID-open FIDopen set alert-dist-open alertdistopen set flush-dist-moved-open flushdistmovedopen
     set FID-cover FIDcover set alert-dist-cover alertdistcover set flush-dist-moved-cover flushdistmovedcover
     set nesthab-prob-1 calc-1 set nesthab-prob-2 calc-2 set nesthab-prob-3 calc-3 set nesthab-prob-4 calc-4 set nesthab-prob-5 calc-
5 ;save these parameters in case of renesting attempt
     set nest-attempt 1 find-nest-location calc-1 calc-2 calc-3 calc-4 calc-5]
end

to find-nest-location [calc-1 calc-2 calc-3 calc-4 calc-5] ;both when initially creating birds and when birds renest if disturbed too much
   let nestcalc random-float 1
   ;nest calc assigns nesting habitat based on stacking probabilities of nesting in various habitat types
   if nestcalc < calc-1 [set nesthab "honey_relict"]
   if nestcalc >= calc-1 and nestcalc < calc-2 [set nesthab "honey_young"]
   if nestcalc >= calc-2 and nestcalc < calc-3 [set nesthab "native_relict"]
   if nestcalc >= calc-3 and nestcalc < calc-4 [set nesthab "native_young"]
   if nestcalc >= calc-4 and nestcalc < calc-5 [set nesthab "open_relict"]
   if nestcalc >= calc-5 [set nesthab "open_young"]
   ;habitat is assigned, move bird to its home for the simulation
   let homehab nesthab move-to one-of patches with [habitat = homehab and not any? turtles in-radius 5] set nestloc patch-here
end

to setup-globals ;establish circadian rhythms and time of day, tell birds not to forage yet
  set time-until-rest 865 set time-until-forage 355 set foraging false set time-of-day 0  ;simulations start at midnight
  ;override probabilities of different types of recreationists entering at any time, useful for scenario testing but not if you want to change
probabilities throughout the day
  if MixType = "Biker" [set probabilities [1 0 0 0]]
  if MixType = "Birder" [set probabilities [0 0 1 0]]
  if MixType = "Hiker" [set probabilities [0 1 0 0]]
  if MixType = "Jogger" [set probabilities [0 0 0 1]]
  if MixType = "Even" [set probabilities [0.25 0.25 0.25 0.25]]
  if MixType = "Birders and Bikers"[set probabilities [0.5 0 0.5 0]]
  if MixType = "Bikers and Joggers"[set probabilities [0.5 0 0 0.5]]
```

```
  set calc-utility-interval 10 ;minute interval at which recs will calculate utility, see User Guidance #17
end

to change-patch-color-disturbance ;this will be called any time a bird is disturbed if visualize-disturbance is on
  ifelse [habitat] of patch-here = "trail" ; turns patches redder if disturbance occurs
     [ifelse pcolor = brown or pcolor = 52 [set pcolor 12.2][set pcolor pcolor + 0.1 if pcolor > 19 [set pcolor 19]]] ;if a trail of cell, convert
to dark red first
     [ifelse pcolor = 10 [set pcolor 12] [set pcolor pcolor + 0.1 if pcolor > 19 [set pcolor 19]]]
end

;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;
;Procedures that occur every timestep. After you click the "go" button in the interface, these will be repeated until the end of the
simulation

to go ;each of the main procedures that run every timestep. main procedures will call subprocedures.
  check-time-of-day
  manage-humans
  manage-birds
  tick ;keep track of timesteps -- move to the next one
  if remainder ticks 1440 = 0 [set day day + 1 if nests-fail? [check-nest-failure]] ;change to the next day. if nest failure is on, nest failure
is checked here
  if ticks >= 30240 [stop] ; end simulation. 21 day simulation, 1440 timesteps per day, 30240 timesteps per simulation
end

;############################################## UPDATE TIME OF DAY
to check-time-of-day ;control bird circadian rhythms and human densities by time of day
    ifelse foraging = true ;birds forage for 865 timesteps and then rest for 575 timesteps every day, birds are active from 5:55 am to 8:15
pm
  [set time-until-forage 575 ; count down time until birds start sleeping
       if time-until-rest > 0 [set time-until-rest time-until-rest - 1]
       if time-until-rest = 0 [set foraging false]]
  [set time-until-rest 865 ; count down time until birds start foraging
```

```
      if time-until-forage > 0 [set time-until-forage time-until-forage - 1]
      if time-until-forage = 0 [set foraging true]]
  ; additional modifier for how many humans overall enter the simulation based on time of day. see User Guidance #1 and #2
  if remainder ticks 1440 < 360 or remainder ticks 1440 >= 1320 [ ;12 am to 6 am and 10 pm to 12 am
    ifelse remainder day 7 = 6 or remainder day 7 = 0 [set time-of-day 0 set period-of-day "weekend night"][set time-of-day 0 set period-of-day "night"]] ;Days 0 and 6 / 7 and 13 / 14 and 20 are weekends
  if remainder ticks 1440 >= 360 and remainder ticks 1440 < 540 [ ;6 am to 9 am
    ifelse remainder day 7 = 6 or remainder day 7 = 0 [set time-of-day 0.15 set period-of-day "weekend early morning"][set time-of-day 0.15 set period-of-day "early morning"]]
  if remainder ticks 1440 >= 540 and remainder ticks 1440 < 720 [ ;9 am to 12 pm
    ifelse remainder day 7 = 6 or remainder day 7 = 0 [set time-of-day 0.3 set period-of-day "weekend late morning"][set time-of-day 0.3 set period-of-day "late morning"]]
  if remainder ticks 1440 >= 720 and remainder ticks 1440 < 900 [ ;12 pm to 3 pm
    ifelse remainder day 7 = 6 or remainder day 7 = 0 [set time-of-day 0.5 set period-of-day "weekend early afternoon"][set time-of-day 0.5 set period-of-day "early afternoon"]]
  if remainder ticks 1440 >= 900 and remainder ticks 1440 < 1140 [ ;3 pm to 7 pm
    ifelse remainder day 7 = 6 or remainder day 7 = 0 [set time-of-day 1 set period-of-day "weekend late afternoon"][set time-of-day 1 set period-of-day "late afternoon"]]
  if remainder ticks 1440 >= 1140 and remainder ticks 1440 < 1320 [ ;7 pm to 10 pm
    ifelse remainder day 7 = 6 or remainder day 7 = 0 [set time-of-day 0.3 set period-of-day "weekend evening"][set time-of-day 0.3 set period-of-day "evening"]]
end

;############################################# MANAGE HUMANS
to manage-humans
  if human-type = "SODA" [ ;blink in and out according to time of day as was done in the SODA study, note that in SODA humans can have persistence, this just was not done for the Fort Harrison study
    ask humans [die] ;remove humans from previous timestep
    let num-humans round max-humans * time-of-day ;calculate appropriate number, see User Guidance #4
    create-humans num-humans [set color black set shape "person" set size 8 move-to one-of patches with [habitat = "trail"]] ;create at random trail locations
    ask humans [cause-disturbance]] ;and stay until next timestep
```

```
  if human-type = "Naive" [ ;naive humans will move along trails but lack much of the complexity of adaptive humans
   let num-humans round max-humans * time-of-day ;calculate appropriate number, see User Guidance #4
    if count humans < num-humans and random-float 1 < 0.5 [create-recreationist] ;if the simulation is not full of humans, chance of adding a single recreationist, see User Guidance #12
    ask humans [check-if-time-to-leave]
    repeat 20 [ ;sequence humans to move in mini-timesteps so that they are more or less moving continuously rather than each human moving an entire timestep's distance at once
     ask humans [
      repeat speed / 20 [ ;20 is used because all human speed values are multiples of 20 with 20 being the lowest
        if minutes-present >= time-budget [set leaving TRUE set color red] ;leave if they are running out of time, change of color is an easy way to see they are leaving
        ifelse leaving [catch-at-intersection-leaving][catch-at-intersection] ;if at intersection ensure fair movement
        let destination min-one-of neighbors with [habitat = "trail"][abs turn-amount] ;move to next patch along trail
        face destination move-to destination set dist-moved dist-moved + 1
        if patch-here = patch 126 407 or patch-here = patch 545 249 [if dist-moved > 5 [die]] ;leave if back to entry point
        cause-disturbance
        ]]]
    ask humans [set minutes-present minutes-present + 1]]

  if human-type = "Adaptive" [ ;adaptive humans have all of the possible adaptive traits
   ;^^^ create humans
    let num-humans round max-humans * time-of-day ;calculate appropriate number, see User Guidance #4
    if count humans < num-humans and random-float 1 < 0.5 [create-recreationist] ;if the simulation is not full of humans, chance of adding a single recreationist, see User Guidance #12
    ;remove memory of encountering other agents put in place to not give immediate repeat encounters. so if they encounter the same person later on it will count again.
   ;^^^ at beginning of timestep: reset a couple parameters, check if time to leave
    ask humans [if ticks - last-encounter-time > 1 [set last-encounter-agentset nobody]
      ;resets speed to default in case they sped up/slowed down due to encounters with other recreationists, see User Guidance #5
      if rec-type = "biker" [set speed 200] if rec-type = "jogger" [set speed 80] if rec-type = "hiker" [set speed 40] if rec-type = "birder" [ifelse leaving = TRUE [set speed 40][set speed 20]]
    check-if-time-to-leave]
   ;begin mini-timesteps
```

```
    repeat 20 [ ;sequence humans to move in mini-timesteps so that they are more or less moving continuously rather than each human moving an entire timestep's distance at once
      ask humans [
        repeat speed / 20 [ ;20 is used because all human speed values are multiples of 20 with 20 being the lowest
  ;^^^ what to do if watching a bird
          if watching-bird? = true [ ;chance per mini-timestep (3 seconds) to stop watching a bird and resume moving along trails from previous patch and heading, see User Guidance #9
            let normalize-speed speed / 20 ;normalization to make sure the chance to start moving will be equal across all speeds: at scale of 3 seconds
             if rec-type = "birder" [ifelse leaving = false ;for birders
               [if random-float 1 < (0.05 / normalize-speed) [set watching-bird? false resume-movement]] ;chance per mini-timestep to start moving again after watching a bird: normal
               [if random-float 1 < (0.2 / normalize-speed) [set watching-bird? false resume-movement]]] ;chance when leaving the park
             if rec-type = "hiker" [ifelse leaving = false  ;for hikers
               [if random-float 1 < (0.1 / normalize-speed) [set watching-bird? false resume-movement]] ;chance per mini-timestep to start moving again after watching a bird: normal
               [if random-float 1 < (0.3 / normalize-speed) [set watching-bird? false resume-movement]]]] ;chance when leaving the park
  ;^^^ what to do if not watching a bird
          if watching-bird? = false [
  ;^^^ move
           ifelse leaving [catch-at-intersection-leaving][catch-at-intersection] ;if at intersection ensure fair movement
           let destination min-one-of neighbors with [habitat = "trail"][abs turn-amount] ;move to next patch along trail
           face destination move-to destination set dist-moved dist-moved + 1
  ;^^^ track cells moved and encounters with other recreationists
           if any? other humans in-radius 0 [track-encounters] ;track encounters if in same place as other human
           if guarded != false [check-guard-off] ;check if time to remove guard
           track-cell-trailtype if rec-type = "biker" and pcolor = 52 and distance min-one-of patches with [pcolor = brown] [distance myself] > 3 [error "oops"] ;biker went off trail
  ;^^^ leave sim if at exit and time is up
           if patch-here = patch 126 407 or patch-here = patch 545 249 [if dist-moved > 5 ;leave if back to entry point
             [if leaving = TRUE and rec-type = "birder" [set num-left num-left + 1 set total-leaving-time total-leaving-time + (minutes-present - time-budget) ;see User Guidance #14
                 set avg-leaving-time total-leaving-time / num-left] ;(minutes-present / sum bird-list)
```

```
            if leaving = TRUE [ ;add accumulated utility to global tracker depending on rec-type, also add to lists if staying longer than original budget
             if rec-type = "biker" [set cumul-biker-util cumul-biker-util + overall-utility if time-budget > orig-time-budget [set bikers-stayed-extra bikers-stayed-extra + 1]]
             if rec-type = "hiker" [set cumul-hiker-util cumul-hiker-util + overall-utility if time-budget > orig-time-budget [set hikers-stayed-extra hikers-stayed-extra + 1]]
             if rec-type = "birder" [set cumul-birder-util cumul-birder-util + overall-utility if time-budget > orig-time-budget [set birders-stayed-extra birders-stayed-extra + 1]]
             if rec-type = "jogger" [set cumul-jogger-util cumul-jogger-util + overall-utility if time-budget > orig-time-budget [set joggers-stayed-extra joggers-stayed-extra + 1]]]
            die]]
    ;^^^ cause disturbance and watch birds
        if random-float 1 < 0.018 [cause-disturbance] ;0.018 leads to about the same amount of disturbance as SODA-type humans, see User Guidance #13
        if rec-type = "birder" or rec-type = "hiker" [if guarded = false [bird-watch]] ;will not watch birds if guard from encountering other recreationists is on
        ]]]] ; end mini-timesteps
    ;update things at end of timestep
     ask humans [set minutes-present minutes-present + 1 ;keeps track of how long humans have been in the park, to compare to time budget
              if remainder minutes-present calc-utility-interval = 0 [calculate-utility]]] ;calculate utility according to the global interval

  set human-timesteps human-timesteps + count humans
end

;******************************************* Creating and parameterizing recreationists
to create-recreationist
  ;lists for each probabilities of each type of recreationist by time of day
  ;from bikers to hikers to birders to joggers
  ;example: [0.3 0.25 0.15 0.2] means a 30% chance of bikers, 25% chance of hikers, 15% chance of birders, 20% chance of joggers at that time of day
  ;you can add more times of day by adding one line here and changing the check-time-of-day procedure by adding a new period of time
 ; if period-of-day = "night" [set probabilities        [0.25 0.25 0.25 0.25]] ;see User Guidance #3
```

```
; if period-of-day = "early morning" [set probabilities   [0.25 0.25 0.25 0.25]]
; if period-of-day = "late morning" [set probabilities    [0.25 0.25 0.25 0.25]]
; if period-of-day = "early afternoon" [set probabilities [0.25 0.25 0.25 0.25]]
; if period-of-day = "late afternoon" [set probabilities  [0.25 0.25 0.25 0.25]]
; if period-of-day = "evening" [set probabilities         [0.25 0.25 0.25 0.25]]
; if period-of-day = "weekend night" [set probabilities           [0.25 0.25 0.25 0.25]]
; if period-of-day = "weekend early morning" [set probabilities   [0.25 0.25 0.25 0.25]]
; if period-of-day = "weekend late morning" [set probabilities    [0.25 0.25 0.25 0.25]]
; if period-of-day = "weekend early afternoon" [set probabilities [0.25 0.25 0.25 0.25]]
; if period-of-day = "weekend late afternoon" [set probabilities  [0.25 0.25 0.25 0.25]]
; if period-of-day = "weekend evening" [set probabilities         [0.25 0.25 0.25 0.25]]
; set probabilities [0 1 0 0] ;or just overwrite
 let bike-cutoff item 0 probabilities
 let hike-cutoff bike-cutoff + item 1 probabilities
 let bird-cutoff hike-cutoff + item 2 probabilities
 if precision (1 - bird-cutoff) 2 != item 3 probabilities [error "Probabilities do not add up to 1."] ;floating point math may lead you to get this error when you should not. if so just comment this out

 let determine-type random-float 1 ;random number between 0 and 1 to compare to above probabilities, this will determine type of created recreationist
     if determine-type < bike-cutoff
     ;create 1 of 4 types of recreationists and set parameters, see User Guidance #5, #7 and #19
       [create-humans 1 [set color black set shape "bike" set size 15 set rec-type "biker" set speed 200 determine-time-budget set bird-list [0 0 0 0 0 0 0 0 0] set watching-bird? false
         ifelse random-float 1 < 0.5 [move-to patch 126 407][move-to patch 545 249] set entry-point patch-here set leaving FALSE set last-encounter-agentset nobody set bird-agentset nobody
         set bad-ts-threshold 2 set trail-type-cell-list [0 0 0 0 0 0 0 0] set guarded false set guarded-against nobody set num-bikers num-bikers + 1]]
     if determine-type >= bike-cutoff and determine-type < hike-cutoff
       [create-humans 1 [set color black set shape "person" set size 8 set rec-type "hiker" set speed 40 determine-time-budget set bird-list [0 0 0 0 0 0 0 0 0] set watching-bird? false
         ifelse random-float 1 < 0.5 [move-to patch 126 407][move-to patch 545 249] set entry-point patch-here set leaving FALSE set last-encounter-agentset nobody set bird-agentset nobody
```

```
        set bad-ts-threshold 2 set singlebird-prob-detect 0.1 set multibird-prob-detect 0.1 set trail-type-cell-list [0 0 0 0 0 0 0 0] set guarded false set guarded-against nobody set beta-substitution random-float 2 - 1 set num-hikers num-hikers + 1]]
   if determine-type >= hike-cutoff and determine-type < bird-cutoff
     [create-humans 1 [set color black set shape "person student" set size 8 set rec-type "birder" set speed 20 determine-time-budget set bird-list [0 0 0 0 0 0 0 0 0] set watching-bird? false
        ifelse random-float 1 < 0.5 [move-to patch 126 407][move-to patch 545 249] set entry-point patch-here set leaving FALSE set last-encounter-agentset nobody set bird-agentset nobody
        set bad-ts-threshold 3 set singlebird-prob-detect 0.9 set multibird-prob-detect 0.5 set trail-type-cell-list [0 0 0 0 0 0 0 0] set guarded false set guarded-against nobody set num-birders num-birders + 1]]
   if determine-type >= bird-cutoff
     [create-humans 1 [set color black set shape "footprint human" set size 12 set rec-type "jogger" set speed 80 determine-time-budget set bird-list [0 0 0 0 0 0 0 0 0] set watching-bird? false
        ifelse random-float 1 < 0.5 [move-to patch 126 407][move-to patch 545 249] set entry-point patch-here set leaving FALSE set last-encounter-agentset nobody set bird-agentset nobody
        set bad-ts-threshold 2 set trail-type-cell-list [0 0 0 0 0 0 0 0] set guarded false set guarded-against nobody set num-joggers num-joggers + 1]]
end

to determine-time-budget ;assign time to stay in park based on normal distribution, can be unique based on type of recreationist, see User Guidance #6
  if rec-type = "biker" [set time-budget round random-normal 60 10 set orig-time-budget time-budget set max-time-budget 90] ;for time-budget: first value mean, second value stdev
  if rec-type = "hiker" [set time-budget round random-normal 60 10 set orig-time-budget time-budget set max-time-budget 90] ; save orig-time-budget to determine if they leave early later on
  if rec-type = "birder" [set time-budget round random-normal 90 15 set orig-time-budget time-budget set max-time-budget 120] ;max-time-budget is the point beyond which they cannot extend their stay, see User Guidance #18 which is in between #11 and #12
  if rec-type = "jogger" [set time-budget round random-normal 60 10 set orig-time-budget time-budget set max-time-budget 90]

  ;also assign the average time it would take that type of recreationist to leave, see User Guidance #14
  ;recalibration of these values would probably be a good idea when survey parameters have been filled in
  ifelse old-trails-included?
    [if rec-type = "biker" [set leaving-time 4] ;time taken to leave when old trails are included
     if rec-type = "hiker" [set leaving-time 20]
```

```
       if rec-type = "birder" [set leaving-time 20]
       if rec-type = "jogger" [set leaving-time 9]
      ]
      [if rec-type = "biker" [set leaving-time 4] ;time taken to leave when old trails are not included
       if rec-type = "hiker" [set leaving-time 27]
       if rec-type = "birder" [set leaving-time 32]
       if rec-type = "jogger" [set leaving-time 12]
      ]
  ; initial calibration of average time to leave (old trails not included / included):
  ;4/4 ts bikers, 12/9 joggers, 27/20 hikers, 32/20 birders (hikers and birders not stopping to watch birds on way out)
end

;******************************************** Rules for movement and leaving
; computes the turn the calling turtle would have to make to face this patch, appropriated from Surface Walking 2D model
; used to get humans to follow the trails
to-report turn-amount  ;
  let this-patch self
  report [subtract-headings (towards this-patch) heading] of myself
end

to catch-at-intersection
  ; catch recreationists at trail intersections and let them move forward in either direction, otherwise they may always move in one
direction
  if patch-here = patch 516 254 [if heading = 315 and random-float 1 < 0.5 [set heading 225]]
  if patch-here = patch 515 254 [ifelse heading = 0 [if random-float 1 < 0.5 [set heading 90]] [if random-float 1 < 0.5 [set heading 180]]]
  if patch-here = patch 515 255 [if heading = 135 and random-float 1 < 0.5 [set heading 180]]
  if patch-here = patch 28 195 [if heading = 0 or heading = 135 [if random-float 1 < 0.5 [set heading 90]]]
  if patch-here = patch 28 196 [if heading = 270 and random-float 1 > 0.5 [set heading 180]]
  if patch-here = patch 127 382 [if heading = 135 [ifelse random-float 1 > 0.5 [set heading 180][set heading 90]]]
  ; catch recreationists at NW entrance and make movement better
  if patch-here = patch 115 394 [if heading = 225 [set heading 180]]
  if patch-here = patch 117 398 [if heading = 225 [ifelse random-float 1 < 0.5 [set heading 180][set heading 270]]]
  if patch-here = patch 110 395 [if heading = 90 and random-float 1 < 0.5 [set heading 0]]
```

```
  if patch-here = patch 111 395 [if heading = 315 [ifelse random-float 1 < 0.5 [set heading 0][set heading 270]]]
  ; prevent humans from leaving simulations before time budget is up
  if patch-here = patch 518 253 [if heading = 90 [set heading 270] if heading = 135 [set heading 315]]
  if patch-here = patch 119 400 and dist-moved > 30 [ifelse random-float 1 < 0.5 [set heading 270][set heading 225]]

  if old-trails-included? [ ;only called if the Trail A trails are included
    if rec-type != "biker" [ ;bikers can't go on the old trails
    if patch-here = patch 151 368 [if heading > 0 and random-float 1 < 0.5 [set heading 180]]
    if patch-here = patch 172 386 [if heading = 45 and random-float 1 < 0.5 [set heading 90]]
    if patch-here = patch 173 386 [if heading = 225 and random-float 1 < 0.5 [set heading 90]]
    if patch-here = patch 160 174 [if heading = 225 and random-float 1 < 0.5 [set heading 135]]
    if patch-here = patch 161 173 [if heading = 315 and random-float 1 < 0.5 [set heading 270]]
    if patch-here = patch 160 173 [if heading = 90 and random-float 1 < 0.5 [set heading 0]]
    if patch-here = patch 291 73 [if heading != 225 and random-float 1 < 0.5 [set heading 45]]
    if patch-here = patch 356 162 [if heading = 270 and random-float 1 < 0.5 [set heading 180]]
    if patch-here = patch 356 161 and random-float 1 < 0.5 [if heading = 135 [set heading 90] if heading = 45 [set heading 315]]
    if patch-here = patch 511 260 [if heading = 315 and random-float 1 < 0.5 [set heading 225]]
    if patch-here = patch 510 260 and random-float 1 < 0.5 [if heading = 315 [set heading 225] if heading = 135 [set heading 225]]
    ]
    if patch-here = patch 160 173 or patch-here = patch 161 173 [if rec-type = "biker" [ ;bikers will enter lower left junction of Trail A
trail by chance
        if heading = 315 [set heading 270]]]
  ]
end

to check-if-time-to-leave ;compare how long they have been in the simulation to their time budgets and the time it would take to leave,
decide if they need to head out
  if leaving = FALSE [
    if minutes-present >= (time-budget - leaving-time) [set leaving TRUE set color red if rec-type = "birder" [set speed 40]]]
end

to catch-at-intersection-leaving ; when humans are at intersections, this will point them towards their exit
  ; otherwise they will go all over the place or never reach the exit
```

```
  if patch-here = patch 515 254 or patch-here = patch 515 255 [ifelse entry-point = patch 126 407 [set heading 315][set heading 90]]
  if patch-here = patch 28 195 or patch-here = patch 28 196 [ifelse entry-point = patch 126 407 [set heading 0][set heading 180]]
  if patch-here = patch 127 382 or patch-here = patch 127 383 [ifelse entry-point = patch 126 407 [set heading 315][set heading 45]]
  if patch-here = patch 111 395 or patch-here = patch 111 396 [ifelse entry-point = patch 126 407 [set heading 0][set heading 135]]
  if patch-here = patch 114 393 or patch-here = patch 114 394 [ifelse entry-point = patch 126 407 [set heading 45][set heading 135]]
  if patch-here = patch 225 98 [ifelse entry-point = patch 126 407 [set heading 270][set heading 90]] ;midway point on South trail so they don't go all the way around
  if patch-here = patch 334 396 [ifelse entry-point = patch 126 407 [set heading 0][set heading 180]] ;midway point on North trail so they don't go all the way around

  if old-trails-included? [ ;only called if the Trail A trails are included
    if rec-type != "biker" [ ;bikers can't go on old trails
    if patch-here = patch 174 386 or patch-here = patch 174 387 or patch-here = patch 174 388 [ifelse entry-point = patch 126 407 [set heading 225][set heading 45]]
    if patch-here = patch 151 368 [ifelse entry-point = patch 126 407 [set heading 270][set heading 90]]
    if patch-here = patch 160 173 or patch-here = patch 160 174 [ifelse entry-point = patch 126 407 [set heading 0][set heading 135]]
    if patch-here = patch 292 74 or patch-here = patch 292 73 or patch-here = patch 292 72 [ifelse entry-point = patch 126 407 [set heading 315][set heading 135]]
    if patch-here = patch 356 161 [ifelse entry-point = patch 126 407 [set heading 315][set heading 45]]
    if patch-here = patch 510 259 or patch-here = patch 510 260 or patch-here = patch 510 261 [ifelse entry-point = patch 126 407 [set heading 0][set heading 90]]
    ]
    if patch-here = patch 160 173 or patch-here = patch 161 173 [if rec-type = "biker" [ ; stop bikers from going up convenient trail
      ifelse entry-point = patch 126 407 [set heading 270] [set heading 135]
    ]]]
end

to track-cell-trailtype ;humans record how many cells they have traveled along different trail segments
  if guarded = false [ ;if utility guard is active, humans will not append to this list while encountered human is still close to them
  if [trail-type] of patch-here = "South" [set trail-type-cell-list replace-item 0 trail-type-cell-list (item 0 trail-type-cell-list + 1)]
  if [trail-type] of patch-here = "North" [set trail-type-cell-list replace-item 1 trail-type-cell-list (item 1 trail-type-cell-list + 1)]
  if [trail-type] of patch-here = "East Access" [set trail-type-cell-list replace-item 2 trail-type-cell-list (item 2 trail-type-cell-list + 1)]
  if [trail-type] of patch-here = "Camp Glenn" [set trail-type-cell-list replace-item 3 trail-type-cell-list (item 3 trail-type-cell-list + 1)]
```

```
  if [trail-type] of patch-here = "Old Central" [set trail-type-cell-list replace-item 4 trail-type-cell-list (item 4 trail-type-cell-list + 1)]
  if [trail-type] of patch-here = "Old East" [set trail-type-cell-list replace-item 5 trail-type-cell-list (item 5 trail-type-cell-list + 1)]
  if [trail-type] of patch-here = "Old West" [set trail-type-cell-list replace-item 6 trail-type-cell-list (item 6 trail-type-cell-list + 1)]
  if [trail-type] of patch-here = "Old South" [set trail-type-cell-list replace-item 7 trail-type-cell-list (item 7 trail-type-cell-list + 1)]]
end

;********************************************* Interact with other humans
to track-encounters ;this was very tricky to write. NetLogo is not conducive to this type of thing.
  ;function tracks the number of encounters with other recreationists, from behind and head-on, updates counters both for the passer and the passee
  ;issues: encounters may be slightly off near trail intersections due to sequenced rather than continuous movement
  ;        when recreationists pass they may be one cell away rather than in the same cell (rare, ~10% of all encounters)
  let passer self
  let going [heading] of self
  set encountering "current"
  let passer-as-set humans with [encountering = "current"]
  set encountering "nope"
  let encountered-as-set other humans in-radius 0

  ifelse last-encounter-agentset = nobody  ;nobody encountered yet to worry about
    [set last-encounter-agentset encountered-as-set set last-encounter-time ticks
    let identification [self] of last-encounter-agentset
    foreach identification [ [?1] -> ;update trackers for passer
      if [rec-type] of ?1 = "biker" [set biker-encounters biker-encounters + 1]
      if [rec-type] of ?1 = "hiker" [set hiker-encounters hiker-encounters + 1]
      if [rec-type] of ?1 = "birder" [set birder-encounters birder-encounters + 1]
      if [rec-type] of ?1 = "jogger" [set jogger-encounters jogger-encounters + 1]
      if utility-guard [guard-on ?1 "NA"] ] ;go to guard-on procedure if utility-guard is switched on
    ask encountered-as-set [ ;update trackers for passee
      let passed-by [rec-type] of passer
      if passed-by = "biker" [ifelse heading != going [set biker-encounters biker-encounters + 1][set biker-enc-behind biker-enc-behind + 1 adapt-speed passer]]
```

```
  if passed-by = "hiker" [ifelse heading != going [set hiker-encounters hiker-encounters + 1][set hiker-enc-behind hiker-enc-behind + 1 adapt-speed passer]]
  if passed-by = "birder" [ifelse heading != going [set birder-encounters birder-encounters + 1][set birder-enc-behind birder-enc-behind + 1 adapt-speed passer]]
  if passed-by = "jogger" [ifelse heading != going [set jogger-encounters jogger-encounters + 1][set jogger-enc-behind jogger-enc-behind + 1 adapt-speed passer]]
  ifelse last-encounter-agentset = nobody [set last-encounter-agentset passer-as-set][set last-encounter-agentset (turtle-set passer-as-set last-encounter-agentset)]
  if utility-guard [guard-on passer going] ;add guard to people encountered as well
  set last-encounter-time ticks]]

 ;allows for encounters when encounter memory is not empty, e.g. encountering multiple people simultaneously
 [let identification [self] of encountered-as-set
  foreach identification [ [?1] -> ;update trackers for passer
  if not member? ?1 last-encounter-agentset [ ;will only count encounter if they have not encountered recently
  set last-encounter-agentset (turtle-set ?1 last-encounter-agentset) set last-encounter-time ticks
  if [rec-type] of ?1 = "biker" [set biker-encounters biker-encounters + 1]
  if [rec-type] of ?1 = "hiker" [set hiker-encounters hiker-encounters + 1]
  if [rec-type] of ?1 = "birder" [set birder-encounters birder-encounters + 1]
  if [rec-type] of ?1 = "jogger" [set jogger-encounters jogger-encounters + 1]
  if utility-guard [guard-on ?1 "NA"] ;go to guard-on procedure if utility-guard is switched on
  ask ?1 [ ;  ;update trackers for passee
   let passed-by [rec-type] of passer
   if passed-by = "biker" [ifelse heading != going [set biker-encounters biker-encounters + 1][set biker-enc-behind biker-enc-behind + 1 adapt-speed passer]]
   if passed-by = "hiker" [ifelse heading != going [set hiker-encounters hiker-encounters + 1][set hiker-enc-behind hiker-enc-behind + 1 adapt-speed passer]]
   if passed-by = "birder" [ifelse heading != going [set birder-encounters birder-encounters + 1][set birder-enc-behind birder-enc-behind + 1 adapt-speed passer]]
   if passed-by = "jogger" [ifelse heading != going [set jogger-encounters jogger-encounters + 1][set jogger-enc-behind jogger-enc-behind + 1 adapt-speed passer]]
   ifelse last-encounter-agentset = nobody [set last-encounter-agentset passer-as-set][set last-encounter-agentset (turtle-set passer-as-set last-encounter-agentset)]
```

```
      if utility-guard [guard-on passer going] ;add guard to people encountered as well
      set last-encounter-time ticks]]
    ]]
end

to adapt-speed [passer] ;humans slow down when passed from behind, speed up if passing someone else from behind (currently
commented out), see User Guidance #5
  ;ask passer [
  ;speed up if passing others, needs to be in multiples of 20
  ;if rec-type = "biker" [set speed 240] if rec-type = "jogger" [set speed 100] if rec-type = "hiker" [set speed 60] if rec-type = "birder"
[ifelse leaving = TRUE [set speed 60][set speed 40]]
  ;]
  ;slow down if passed from behind, needs to be in multiples of 20
  if rec-type = "jogger" [set speed 60] if rec-type = "hiker" [set speed 20] if rec-type = "birder" [ifelse leaving = TRUE [set speed 20]
[set speed 0]]
end

to guard-on [agent extra] ;put guard on agent after negative encounters to stop accumulation of utility, "agent" is rec-type of recreationist
encountered,
  ;"extra" is the heading of the passing recreationist (when relevant) which determines if passed recs are extra annoyed and take longer
to resume normal activity
  let store-rec-type [rec-type] of agent ;see User Guidance #11
  ask agent [set encountering "current"]
  let agent-as-set humans with [encountering = "current"]
  ask agent [set encountering "nope"]
  if rec-type = "biker" [if store-rec-type = "biker" or store-rec-type = "hiker" or store-rec-type = "birder" or store-rec-type =
"jogger" ;bikers don't like anybody so put guard on no matter who they encounter
    [ifelse extra = heading [set guarded "extra"][set guarded "regular"] ;put guard on with chance to be extra annoyed if passed from
behind
     ifelse guarded-against = nobody [set guarded-against agent-as-set][set guarded-against (turtle-set agent-as-set guarded-
against)]]] ;add agent to list of recs that the guard applies to
  if rec-type = "hiker" [if store-rec-type = "biker" or store-rec-type = "jogger" ;hikers only dislike bikers and joggers
```

```
    [ifelse extra = heading [set guarded "extra"][set guarded "regular"] ;put guard on with chance to be extra annoyed if passed from behind
     ifelse guarded-against = nobody [set guarded-against agent-as-set][set guarded-against (turtle-set agent-as-set guarded-against)]]] ;add agent to list of recs that the guard applies to
  if rec-type = "birder" [if store-rec-type = "biker" or store-rec-type = "jogger" ;birders only dislike bikers and joggers
    [ifelse extra = heading [set guarded "extra"][set guarded "regular"] ;put guard on with chance to be extra annoyed if passed from behind
     ifelse guarded-against = nobody [set guarded-against agent-as-set][set guarded-against (turtle-set agent-as-set guarded-against)]]] ;add agent to list of recs that the guard applies to
  if rec-type = "jogger" [if store-rec-type = "biker" or store-rec-type = "hiker" or store-rec-type = "birder" or store-rec-type = "jogger" ;joggers dislike everybody
    [ifelse extra = heading [set guarded "extra"][set guarded "regular"] ;put guard on with chance to be extra annoyed if passed from behind
     ifelse guarded-against = nobody [set guarded-against agent-as-set][set guarded-against (turtle-set agent-as-set guarded-against)]]] ;add agent to list of recs that the guard applies to
end

to check-guard-off ;remove guard if encountered agents are at least a specified distance away, resume accumulating utility, see User Guidance #11
  if rec-type = "biker" [if guarded = "extra" [if count guarded-against in-radius 7 = 0 [set guarded false set guarded-against nobody]]
     if guarded = "regular" [if count guarded-against in-radius 5 = 0 [set guarded false set guarded-against nobody]]]
  if rec-type = "hiker" [if guarded = "extra" [if count guarded-against in-radius 7 = 0 [set guarded false set guarded-against nobody]]
     if guarded = "regular" [if count guarded-against in-radius 5 = 0 [set guarded false set guarded-against nobody]]]
  if rec-type = "birder" [if guarded = "extra" [if count guarded-against in-radius 7 = 0 [set guarded false set guarded-against nobody]]
     if guarded = "regular" [if count guarded-against in-radius 5 = 0 [set guarded false set guarded-against nobody]]]
  if rec-type = "jogger" [if guarded = "extra" [if count guarded-against in-radius 7 = 0 [set guarded false set guarded-against nobody]]
     if guarded = "regular" [if count guarded-against in-radius 5 = 0 [set guarded false set guarded-against nobody]]]
end

;******************************************* Interact with birds
to cause-disturbance ;can be very computationally intensive if called frequently since this searches a radius of 15 patches for every single cell moved by a human
  let disturber self
```

```
  let location patch-here
  let disturbed-birds birds in-radius 15 ;15 here represents the largest alert distance of a particular species (Ovenbird) and so the largest distance needed to check
  if disturbed-birds != "nobody" [
    ask disturbed-birds [
     ifelse [habitat] of patch-here = "open_relict" or [habitat] of patch-here = "open_young" or [habitat] of patch-here = "trail"
      [set curr-patch "open"][set curr-patch "cover"] ;determine whether bird is in covered or open habitat

    if curr-patch = "open" [ ;specify if in open habitat so appropriate alert/FID/flushing values will be applied
      if distance disturber <= alert-dist-open [ ;will be disturbed
        ifelse distance disturber <= FID-open ;will flush
         [set behavior "flushing open" set threat-patch location set threat-agent [rec-type] of disturber determine-threat-type threat-agent ;identify threat for records
          if Visualize-Disturbance [change-patch-color-disturbance] ;call this before the bird flushes to show patch where disturbed
          face threat-patch bk flush-dist-moved-open] ;move away
         [if behavior = "reset" [set behavior "alert" set threat-patch location set threat-agent [rec-type] of disturber]] ;will not change status to alert if already flushing or alert
        ]]
    if curr-patch = "cover" [ ;specify if in cover habitat so appropriate alert/FID/flushing values will be applied
      if distance disturber <= alert-dist-cover [ ;will be disturbed
        ifelse distance disturber <= FID-cover ;will flush
         [set behavior "flushing cover" set threat-patch location set threat-agent [rec-type] of disturber determine-threat-type threat-agent ;identify threat for records
          if Visualize-Disturbance [change-patch-color-disturbance]
          face threat-patch bk flush-dist-moved-cover] ;move away
         [if behavior = "reset" [set behavior "alert" set threat-patch location set threat-agent [rec-type] of disturber]]
        ]]]]
end

to bird-watch
  ; following line will clear hidden birdlist (not the one used for utility calculations) when not seeing any birds so they can detect a bird if they pass it in the future, may want to experiment with value of 5
  ;if last-bird-enc-time != 0 [if ticks - last-bird-enc-time >= 5 [set bird-agentset nobody]]
```

```
  ; detect birds, detection radius can change every timestep
  let detection-radius-birders random-normal 10 2 ;see User Guidance #7
  let detection-radius-hikers random-normal 5 1
  if rec-type = "birder" [ifelse detection-radius-birders > 0 [set bird-detect-radius detection-radius-birders][set bird-detect-radius 0]] ;prevents error when this result comes back as a negative value
  if rec-type = "hiker" [ifelse detection-radius-hikers > 0 [set bird-detect-radius detection-radius-hikers][set bird-detect-radius 0]]
  set birds-detected birds in-radius bird-detect-radius
  if any? birds-detected and random-float 1 < singlebird-prob-detect [ ; chance of detecting a bird given that it is within a certain distance
    set last-bird-enc-time ticks
    if count birds-detected > 1 and random-float 1 > multibird-prob-detect [set birds-detected n-of 1 birds-detected] ;chance of detecting more than one bird at a time, otherwise choose one bird that human will detect
     ifelse bird-agentset = nobody ;bird-agentset is their hidden list that keeps them from counting a single bird multiple times
      [let bird-ID [self] of birds-detected foreach bird-ID [ [?1] ->
        if [species] of ?1 = "Ovenbird" [set bird-list replace-item 0 bird-list (item 0 bird-list + 1)] ;updates birdlists used in utility calculations
        if [species] of ?1 = "Hooded Warbler" [set bird-list replace-item 1 bird-list (item 1 bird-list + 1)]
        if [species] of ?1 = "Carolina Chickadee" [set bird-list replace-item 2 bird-list (item 2 bird-list + 1)]
        if [species] of ?1 = "Brown Creeper" [set bird-list replace-item 3 bird-list (item 3 bird-list + 1)]
        if [species] of ?1 = "Downy Woodpecker" [set bird-list replace-item 4 bird-list (item 4 bird-list + 1)]
        if [species] of ?1 = "Acadian Flycatcher" [set bird-list replace-item 5 bird-list (item 5 bird-list + 1)]
        if [species] of ?1 = "Kentucky Warbler" [set bird-list replace-item 6 bird-list (item 6 bird-list + 1)]
        if [species] of ?1 = "Eastern Wood Pewee" [set bird-list replace-item 7 bird-list (item 7 bird-list + 1)]
        if [species] of ?1 = "Wood Thrush" [set bird-list replace-item 8 bird-list (item 8 bird-list + 1)]
        set bird-agentset (turtle-set ?1 bird-agentset) ;adds bird to hidden list
        if rec-type = "birder" [
          ifelse leaving = true
            [if random-float 1 < 0.25 [stalk-bird set watching-bird? true]] ;chance of stopping to watch a bird if a birder and leaving the park, see User Guidance #8
            [if random-float 1 < 0.5 [stalk-bird set watching-bird? true]]] ;chance of stopping to watch a bird if a birder and not currently leaving
        if rec-type = "hiker" [
          ifelse leaving = true
```

```
              [if random-float 1 < 0 [stalk-bird set watching-bird? true]] ;chance of stopping to watch a bird if a hiker and leaving the park
              [if random-float 1 < 0.25 [stalk-bird set watching-bird? true]]] ;chance of stopping to watch a bird if a hiker and not currently
leaving
          ]]
      [let bird-ID [self] of birds-detected foreach bird-ID [ [?1] ->
          if not member? ?1 bird-agentset [ ;cannot count a bird if it is already in their hidden list
            if [species] of ?1 = "Ovenbird" [set bird-list replace-item 0 bird-list (item 0 bird-list + 1)]
            if [species] of ?1 = "Hooded Warbler" [set bird-list replace-item 1 bird-list (item 1 bird-list + 1)]
            if [species] of ?1 = "Carolina Chickadee" [set bird-list replace-item 2 bird-list (item 2 bird-list + 1)]
            if [species] of ?1 = "Brown Creeper" [set bird-list replace-item 3 bird-list (item 3 bird-list + 1)]
            if [species] of ?1 = "Downy Woodpecker" [set bird-list replace-item 4 bird-list (item 4 bird-list + 1)]
            if [species] of ?1 = "Acadian Flycatcher" [set bird-list replace-item 5 bird-list (item 5 bird-list + 1)]
            if [species] of ?1 = "Kentucky Warbler" [set bird-list replace-item 6 bird-list (item 6 bird-list + 1)]
            if [species] of ?1 = "Eastern Wood Pewee" [set bird-list replace-item 7 bird-list (item 7 bird-list + 1)]
            if [species] of ?1 = "Wood Thrush" [set bird-list replace-item 8 bird-list (item 8 bird-list + 1)]
            set bird-agentset (turtle-set ?1 bird-agentset) ;adds bird to hidden list
          if rec-type = "birder" [
            ifelse leaving = true
              [if random-float 1 < 0.25 [stalk-bird set watching-bird? true]] ;chance of stopping to watch a bird if a birder and leaving the
park
              [if random-float 1 < 0.5 [stalk-bird set watching-bird? true]]] ;chance of stopping to watch a bird if a birder and not currently
leaving
          if rec-type = "hiker" [
            ifelse leaving = true
              [if random-float 1 < 0 [stalk-bird set watching-bird? true]] ;chance of stopping to watch a bird if a hiker and leaving the park
              [if random-float 1 < 0.25 [stalk-bird set watching-bird? true]]] ;chance of stopping to watch a bird if a hiker and not currently
leaving
              ] ]]]
  set num-birds-seen sum bird-list
  set num-species-seen species-seen bird-list
  if minutes-present > 0 [set rate-birds-seen num-birds-seen / minutes-present] ;number of birds seen per minute, but don't divide by 0
end
```

```
to stalk-bird ;if recreationists are allowed off trails, move towards detected birds
  if off-trail [
    if watching-bird? = false [set patch-left patch-here set heading-left heading] ;save location on trail to go back to without getting lost
    let bird-of-interest one-of birds-detected
    let distance-away distance bird-of-interest
    face bird-of-interest fd (distance-away / 2) ;move half the distance to detected bird
    cause-disturbance]
end

to resume-movement ;go back to place where they left the trail and resume movement in same direction
  if off-trail = true [move-to patch-left set heading heading-left]
end

to-report species-seen [input-list] ;see primitive "reduce" in NetLogo Dictionary, this will report the number of non-zeros in the bird-
list
  report 9 - reduce [ [?1 ?2] -> ifelse-value (?2 = 0) [?1 + 1] [?1] ] (fput 0 input-list)
end

;******************************************* Utility functions and miscellaneous trackers for input into functions
to calculate-utility
  if rec-type = "biker" [determine-biker-utility]
  if rec-type = "hiker" [determine-hiker-utility]
  if rec-type = "birder" [determine-birder-utility]
  if rec-type = "jogger" [determine-jogger-utility]
end

to determine-biker-utility
  let prev-util overall-utility ;to compare this to new value
;^^^ trail utility
  let trail-cell-vector create-trail-vector 1 1 1 1 1 1 1 ;where each value is a weight for how much recreationists like particular trail
segments, see User Guidance #10
  set trail-utility ln (0.001 * trail-cell-vector)
;^^^ negative utility from encounters with other recreationists
```

```
;  let encounter-vector create-recencounter-vector 1 1 1 1 2 0 0 0 ;where each value is a weight for how much this type of recreationist will be annoyed by encounters of each type
;  if encounter-vector > 0 [set encounter-neg-utility 1 - exp (0.01 * encounter-vector)]
;^^^ overall utility / chance to add time to budget or leave
  set overall-utility trail-utility / 6.935 ;avg 6.935 raw utility per biker on exit, see User Guidance #15
  let marginal-util (overall-utility - prev-util) / calc-utility-interval ;show marginal gain since last calculation
 ; show marginal-util show minutes-present ;count as "bad timestep" if marginal gain around 0
 if marginal-util < 0.0017 and prev-util > 0 and leaving != true and adjustable-time-budget [show "biker bad timestep" set bad-ts bad-ts + 1 if bad-ts >= bad-ts-threshold [ ;leave if enough bad timesteps, see User Guidance #19
    set leaving true set color red show "biker leaving" show minutes-present if minutes-present < orig-time-budget - leaving-time [set bikers-left-early bikers-left-early + 1]]]
 if leaving != true [check-to-extend-stay marginal-util] ;if still in the park and getting close to original time budget, check whether to extend stay
end

to determine-hiker-utility ;estimated 13 minutes to see a bird with minimal negative encounters, 1 unit of bird = (40 cells * 13 minutes) 520 cells traveled
  let prev-util overall-utility ;to compare this to new value
;^^^ trail utility
   let trail-cell-vector (create-trail-vector 1 1 1 1 1 1 1 1) / 520  ;where each value is a weight for how much recreationists like particular trail segments, see User Guidance #10
   set trail-utility ln trail-cell-vector
;^^^ bird utility
   let bird-vector (sum bird-list) ;for simplicity, ignore rarity, number of species, and rate of seeing birds (but see birder utility if this changes)
   if bird-vector > 0 [set bird-utility ln bird-vector]
;^^^ negative utility from encounters with other recreationists
 ;  let encounter-vector create-recencounter-vector 1 0 0 1 2 0 0 2
 ;  if encounter-vector > 0 [set encounter-neg-utility 1 - exp (0.01 * encounter-vector)]
  ;^^^ overall utility / chance to add time to budget or leave
  ;beta-substitution is assigned on entry for each hiker, number between -1 and 1
   set overall-utility (trail-utility + bird-utility + beta-substitution * (trail-utility * bird-utility)) / 3.15 ;avg 3.15 raw utility per birder on exit, see User Guidance #15
```

```
  let marginal-util (overall-utility - prev-util) / calc-utility-interval ;show marginal gain since last calculation
 ;  show marginal-util show minutes-present ;leave early if marginal gain around 0
 ;  if marginal-util < 0.0017 and prev-util > 0 and leaving != true and adjustable-time-budget [show "hiker bad timestep" set bad-ts bad-ts + 1 if bad-ts >= bad-ts-threshold [ ;leave if enough bad timesteps, see User Guidance #19
 ;     set leaving true set color red show "hiker leaving" show minutes-present if minutes-present < orig-time-budget - leaving-time [set hikers-left-early hikers-left-early + 1]]]
 ;  if leaving != true [check-to-extend-stay marginal-util] ;if still in the park and getting close to original time budget, check whether to extend stay
end

to determine-birder-utility
  let prev-util overall-utility ;to compare this to new value
;^^^ bird utility
  let weighted-bird-list item 0 bird-list * 1 + item 1 bird-list * 0.875 + item 2 bird-list * 0.4375 + item 3 bird-list * 0.875 + item 4 bird-list * 0.5
  + item 5 bird-list * 0.333 + item 6 bird-list * 1 + item 7 bird-list * 0.636 + item 8 bird-list * 0.467 ;where numbers are equal to rarity value for each species
  let bird-vector (weighted-bird-list + num-species-seen) ;+ rate-birds-seen * 5,
  if bird-vector > 0 [set bird-utility ln (2.65 * bird-vector)]
;^^^ negative utility from encounters with other recreationists
  ; let encounter-vector create-recencounter-vector 1 0 0 1 2 0 0 2
  ; if encounter-vector > 0 [set encounter-neg-utility 1 - exp (0.01 * encounter-vector)]
;^^^ overall utility / chance to add time to budget or leave
  set overall-utility bird-utility / 2.96 ;avg 2.96 raw utility per birder on exit, see User Guidance #15  let marginal-util (overall-utility - prev-util) / calc-utility-interval ;show marginal gain since last calculation
  let marginal-util (overall-utility - prev-util) / calc-utility-interval ;show marginal gain since last calculation
  ; show marginal-util show minutes-present ;count as "bad timestep" if marginal gain around 0
  if marginal-util < 0.002 and leaving != true and adjustable-time-budget [show "birder bad timestep" set bad-ts bad-ts + 1 if bad-ts >= bad-ts-threshold [ ;leave if enough bad timesteps, see User Guidance #19
    set leaving true set color red show "birder leaving" show time-budget show minutes-present if minutes-present < orig-time-budget - leaving-time [set birders-left-early birders-left-early + 1]]]
  if leaving != true [check-to-extend-stay marginal-util] ;if still in the park and getting close to original time budget, check whether to extend stay
```

```
end

to determine-jogger-utility
    let prev-util overall-utility ;to compare this to new value
;^^^ trail utility
  let trail-cell-vector create-trail-vector 1 1 1 1 1 1 1 1 ;where each value is a weight for how much recreationists like particular trail segments, see User Guidance #10
  set trail-utility ln (0.005 * trail-cell-vector)
;^^^ negative utility from encounters with other recreationists
 ; let encounter-vector create-recencounter-vector 1 1 1 1 2 2 0 0 ;where each value is a weight for how much this type of recreationist will be annoyed by encounters of each type
 ; if encounter-vector > 0 [set encounter-neg-utility 1 - exp (0.01 * encounter-vector)]
;^^^ overall utility / chance to add time to budget or leave
  set overall-utility trail-utility / 1 ;avg 1.67 raw utility per jogger on exit, see User Guidance #15
  let marginal-util (overall-utility - prev-util) / calc-utility-interval ;show marginal gain since last calculation
  ;show marginal-util show minutes-present ;leave early if marginal gain around 0
  if marginal-util < 0.013 and prev-util > 0 and leaving != true and adjustable-time-budget [show "jogger bad timestep" set bad-ts bad-ts + 1 if bad-ts >= bad-ts-threshold [ ;leave if enough bad timesteps, see User Guidance #19
  set leaving true set color red show "jogger leaving" show minutes-present if minutes-present < orig-time-budget - leaving-time [set joggers-left-early joggers-left-early + 1]]]
  if leaving != true [check-to-extend-stay marginal-util] ;if still in the park and getting close to original time budget, check whether to extend stay
end

to check-to-extend-stay [marginal-util] ;when recreationists approach the time when they would leave according to their original time budget, they check to see if their marginal utility increase is still more than 0 (or whatever threshold is specified close to 0)
  ;if so, and if they are not running up against their maximum time budget, they will extend their stay until the next calculation of utility
  if adjustable-time-budget [
    if rec-type = "biker" [if minutes-present >= (time-budget - calc-utility-interval - leaving-time) and time-budget <= max-time-budget - calc-utility-interval - leaving-time
       [if marginal-util > 0.0017 [set time-budget time-budget + calc-utility-interval show "biker extending stay" show time-budget]]] ; 0.0017 is the threshold set in calculate-biker-utility
```

```
   if rec-type = "jogger" [if minutes-present >= (time-budget - calc-utility-interval - leaving-time) and time-budget <= max-time-budget
- calc-utility-interval - leaving-time
      [if marginal-util > 0.013 [set time-budget time-budget + calc-utility-interval show "jogger extending stay" show time-budget]]] ;
0.013 is the threshold set in calculate-jogger-utility
   if rec-type = "hiker" [if minutes-present >= (time-budget - calc-utility-interval - leaving-time) and time-budget <= max-time-budget
- calc-utility-interval - leaving-time
      [if marginal-util > 0.013 [set time-budget time-budget + calc-utility-interval show "hiker extending stay" show time-budget]]] ;
need threshold other than 0.013
   if rec-type = "birder" [if minutes-present >= (time-budget - calc-utility-interval - leaving-time) and time-budget <= max-time-budget
- calc-utility-interval - leaving-time
      [if marginal-util > 0.002 [set time-budget time-budget + calc-utility-interval show "birder extending stay" show time-budget]]]] ;
0.002 is the threshold set in calculate-birder-utility
end

to-report create-recencounter-vector [enc-bikers enc-hikers enc-birders enc-joggers enc-bikers-behind enc-hikers-behind enc-birders-
behind enc-joggers-behind]
  ;takes each of the counts of encounters with other recreationists and applies a weight for how much impact each type would have,
based on a list of 8 numbers assigned when calling this reporter
  let weighted-encounters enc-bikers * biker-encounters + enc-hikers * hiker-encounters + enc-birders * birder-encounters + enc-joggers
* jogger-encounters
  + enc-bikers-behind * biker-enc-behind + enc-hikers-behind * hiker-enc-behind + enc-birders-behind * birder-enc-behind + enc-
joggers-behind * jogger-enc-behind
  report weighted-encounters
end

to-report create-trail-vector [weight-south weight-north weight-eastaccess weight-glenn weight-oldcent weight-oldeast weight-oldwest
weight-oldsouth] ;see User Guidance #10
  ;takes the list of cells recreationists have travelled on different trail segments and multiplies by given weights for trail enjoyment
  let weighted-trail-cells weight-south * item 0 trail-type-cell-list + weight-north * item 1 trail-type-cell-list + weight-eastaccess * item
2 trail-type-cell-list
  + weight-glenn * item 3 trail-type-cell-list + weight-oldcent * item 4 trail-type-cell-list + weight-oldeast * item 5 trail-type-cell-list
  + weight-oldwest * item 6 trail-type-cell-list + weight-oldsouth * item 7 trail-type-cell-list
  report weighted-trail-cells
```

```
end

;############################################  MANAGE BIRDS
to manage-birds ;finalize behavior and move birds that have not flushed
  ask birds [
    if behavior = "flushing open" or behavior = "flushing cover"
     [set energy energy - 0.1 set flush-count flush-count + 1] ;represents energetic loss from flushing

    if behavior = "alert" [if Visualize-Disturbance [change-patch-color-disturbance] ; visualize-disturbance here to make sure only one cell gets turned red per ts if alert
      set alert-count alert-count + 1 determine-threat-type threat-agent]

    if behavior = "reset" [ ;if not disturbed in the last timestep
        ifelse foraging = true
        [set behavior "foraging"] ;forage if foraging time
        [ifelse patch-here = nestloc ;otherwise sleep, or go home if not there
          [set behavior "sleeping"][set behavior "homing"]]]

    if behavior = "sleeping" [] ; do nothing. sounds pretty nice to me.

    if behavior = "homing" [ifelse distance nestloc > 50 ;if not home
     [face nestloc fd 50] [move-to nestloc]] ;move directly home if close, otherwise orient and move towards home

    if behavior = "foraging"
      [ifelse energy < 15 ;will go back to nest at 15 energy
         [set heading heading + random 180 - 90 ;approximates a mildly correlated random walk
            if xcor > 3 and xcor < 564 and ycor > 3 and ycor < 460 [if [pcolor] of patch-ahead 3 = black [rt 180]] ;stay within simulated habitat and don't go off edge of world
            fd 3 set energy energy + 0.2] ;move forward and gain energy
         [ifelse distance nestloc > 50 ;energy is at least 15, go home to feed chicks
            [face nestloc fd 50]
            [move-to nestloc let to-nest energy - 10 set energy 10 ask nests-here [set energy energy + to-nest]]]] ;energy is transferred to nest
```

```
    set behavior "reset" set disturb-count alert-count + flush-count]
end

to check-nest-failure ;nests will check whether they have received enough energy to continue, if not, adults will renest immediately (for consistency in response variables)
   ask nests [set days-present days-present + 1
     if energy / days-present < 150 [set nests-failed nests-failed + 1 ;3490 energy throughout simulation if undisturbed, 166 per day. see User Guidance #16
       ask associated-adult [set nest-attempt nest-attempt + 1 set behavior "renesting" find-nest-location nesthab-prob-1 nesthab-prob-2 nesthab-prob-3 nesthab-prob-4 nesthab-prob-5] ;find new nest location
     die]] ;old nest is removed from simulation

   let new-nests count birds with [behavior = "renesting"] ;count number of new nests to make
   create-nests new-nests [set shape "dot" set size 3 move-to one-of patches with [count birds-here = 1 and [behavior] of one-of birds-here = "renesting"] set color [color] of one-of birds-here
    set associated-adult one-of birds-here set species [species] of one-of birds-here set energy 0 ask associated-adult [set behavior "reset"]]
end

to determine-threat-type [threat] ;when disturbed, birds save the rec-type of the human that disturbed them, and update the relevant counters here
   if threat = "biker" [set dist-by-biker dist-by-biker + 1]
   if threat = "hiker" [set dist-by-hiker dist-by-hiker + 1]
   if threat = "birder" [set dist-by-birder dist-by-birder + 1]
   if threat = "jogger" [set dist-by-jogger dist-by-jogger + 1]
end

;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;
;This is the end of the model
;Please contact the author at sorgarc147@yahoo.com
```