**Overview, Design Concepts, Details**

The model description below follows the ODD protocol (overview, design concepts, details)

for describing agent-based models (Grimm et al. 2020).

***Purpose***

This model was developed to test whether variation in wildland availability, connectivity, and livestock herding practices might explain variation in rates of livestock predation by gray wolves. The questions we investigate are: 1) Does the availability and connectivity of wildland on a landscape impact the rate at which grey wolves encounter and predate upon livestock? and 2) how do different livestock grazing practices exacerbate or alleviate depredation rates across these model landscapes? To examine these questions, we modelled scenarios containing various configurations of wildland availability and connectivity, upon which livestock-agent herds were grazed under three different management practices alongside a wolf-agent pack and a population of wild ungulate-agents.

***Entities, state variables, and scales***

*Scale*

The simulation landscape is 625-km2 arrayed in a 2-dimensional 100 x 100 cell grid (10,000 individual cells), wrapped vertically and horizontally. Each cell emulates a discrete 6.25 ha vegetation patch. The model landscape was built around the average spatial extent over which North American gray wolves roam, as informed by several studies (see Table S1). Our model depicts one, 365-day calendar year, broken into days. Each time step in the model represents a single day.

*Entities*

Patch environment: The model landscape consists of two cell types: wildland and pastureland. Wildland cells represent publicly managed forest or rangeland, typically occupied by various species of wildlife, and often grazed by livestock on an allotment- or permit-level basis. Pastureland cells are representative of privately owned lands managed for livestock and agriculture. The edges of the virtual landscape are wrapped (aka, a torus), enabling all three agent types to move throughout the landscape without encountering edge effects. Prior to running a simulation, each cell is initialized with a randomly assigned number of “meals” for herbivores (wild prey and livestock-agents), ranging from 1 – 1000. These meals are then delineated as either “wildland meals” or “pastureland meals,” depending on the designation of the cell. This meal availability is designed to replicate randomness in vegetation growth across the landscape according to the availability of nutrients, sunlight, water, etc. (Fuhlendorf et al. 2017). The depletion of “meals” within a cell as a result of grazing by wild prey or livestock-agents is designed to emulate a reduction in desirable forage to the extent that motivates the agent to move to a new cell in search of food (Bailey & Brown 2011). The number of meals is not replenished over the course of a simulation run, resulting in a landscape that gradually degrades with each time step. This mimics the natural depletion that occurs over the course of one year in a grazing landscape, beginning with spring “green up” and concluding at the end of winter (Robinson et al. 2019).

Wild prey-agents: these agents simulate the characteristics of ungulate species preyed upon by gray wolves in the Western United States, including elk (*Cervus canadensis*), mule deer (*Odocoileus hemionus*), and white-tailed deer (*Odocoileus virginianus*). In the model, these three ungulate species are represented as a single, “wild prey” species that moves across the landscape as solitary agents. While elk tend to move in herds and mule deer and white-tailed deer live either as solitary individuals or in smaller, multi-generational family groups, wolves typically kill individual prey when hunting, regardless of prey group size. Therefore, we represent prey agents as individuals to measure predation rates in a manner representative of wolf hunting style and kill rates, without specifying prey species’ sociality. The three “active” agents (wolves, wild prey, and livestock) are designed to act in their own best interest, maximizing nutritional intake to suit their reproductive needs. While the time duration of a simulation run (one year) does not allow reproduction to occur, agents are still programmed to behave in a manner that would lead to maximum reproductive success. Similarly, wild prey and livestock mortalities only occur as a result of predation, rather than from disease, age, or lack of resources.

Livestock-agents: this agent-type is designed to represent the movement and behavioral patterns of cattle (*Bos taurus*) herds in the focal region. Recognizing that management of livestock herds varies from operation to operation, we modeled three versions of livestock herding practices that affect grazing patterns:

(1) *free roaming* livestock can move across the landscape unimpeded, grazing on both wildland and pastureland cells. This simulation served as a control to assess the relative effect herding practices that restrict livestock to graze just on farm pastures (*pasture-limited*) or a mixed strategy of both pasture and wildland grazing (*seasonal grazing*) would have on livestock mortality.

(2) *pasture-limited* livestock are restricted to moving across and grazing on pastureland cells only. This treatment was designed to emulate herds grazing entirely on privately held lands with human infrastructure nearby—barns, fencing, residences, etc.

(3) *seasonal grazing* livestock spend the first half of the simulation limited to moving across and grazing on the wildland cells of the fragment they were placed on. Each herd is moved back to their associated farm for the second half of the simulation, where they are limited to moving across and grazing on pastureland. This treatment was designed to emulate the seasonal use of public grazing allotments, whereby livestock producers move their herds to public lands in the spring when forage is high and leave them to graze until the fall (Fleischner 1994; Huntsinger et al. 2010).

Livestock-agents display a fear response to wolf presence regardless of treatment and move across the landscape in a set number of herds with a set number of individuals (Kluever et al. 2008; Laporte et al. 2010). The movement of the herd is driven largely by the herd leader, who acts to maximize their own best interest (moving to cells with the greatest number of available meals). The non-leaders also act in such a manner but will consider their distance from the herd leader prior to engaging in any other processes. Herds can occupy multiple adjacent cells, emulating the distribution of livestock across several acres of land, but individual livestock-agents within each herd can only occupy one cell at a time. Multiple livestock-agents can occur on a single cell at the same time.

If at any point in a simulation run a herd leader agent is killed by wolves, a new livestock-agent from the same herd that is nearest the location where the herd leader agent has died becomes the new herd leader, with the remaining livestock-agents following the new herd leader according to the movement-feeding routine. This ensures continued movement and herding behavior of the livestock-agents.

Wolf-agents: this agent type emulates the movement, behavioral, and predation characteristics of gray wolves living in the American West and can prey upon either the wild prey or livestock-agents. The wolf-agents move across the landscape in a pack, with movement largely driven by the pack leader. To emulate real-world avoidance of human settlements, the wolf-agents will not come within a certain radius of the farm-agents (Theuerkauf 2009; Carricondo-Sanchez et al. 2020). Similarly, the wolves can only make a kill once every three time steps, following average rates of consumption found in the literature (Table S1). Both pack and non-pack leaders can make a kill, but the pack’s prey consumption is linked. If one wolf makes a kill, no wolves will make a kill for the remainder of that day or over next two days.

Farm-agents: completely stationary agents, the farms act as a “home base” for the livestock-agents to begin at under the *free roaming* and *pasture-limited* grazing treatments. Each herd returns to “their” farm (called ‘my-farm’) at time step 183 of the *seasonal grazing* treatment as well. The farms are intended to emulate the presence of livestock operations and their infrastructure on the landscape. The wolf-agents will not approach within a two cell radius of the farms, much as they tend to avoid human settlements in the real world (Theuerkauf 2009; Carricondo-Sanchez et al. 2020). Each farm-agent occupies a single cell and remains stationary throughout the duration of the run. Farm-agents cannot be placed within a ten-cell distance of one another during model initialization, emulating the disparate spacing of privately owned pastureland.

*State variables*

State variables characterizing each agent type and the landscape cells are provided in Table 1.

***Table 1.*** *State variables for the agents and habitat cells in the model.*

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| Entity | Variable | Description | Values & Units | Dynamic or Static |
| Livestock | Herd-leader? | Whether the individual is the herd leader | True/false | Static |
|  | My-leader-cow | Identity of the herd leader for non-leader livestock-agents | 1 – number of herds; unique agents | Static |
|  | Wolf-encounter | Number of times a livestock-agent has sensed a wolf within a one-cell radius of them | 0 – no limit; wolf encounters | Dynamic |
|  | My-farm | Identity of the farm the livestock is from | 1 – 10; individual agents | Static |
| Wolf | Pack-leader? | Whether the individual is the pack leader | True/false | Static |
|  | Leader-wolf | Identity of the pack leader for non-leader wolf-agents | 1 – 6; individual agents | Static |
| Farm | Farm-number | The identity of the farm | 1 – 10; individual agents | Static |
|  | Farm-x | x-coordinate of farm |  | Static |
|  | Farm-y | y-coordinate of farm |  | Static |
| Cell | Patch-avail | If a cell is wildland or pastureland | 0 or 1 | Static |
|  | Patch-meals | Number of meals a wildland cell owns | 0 – 1000; meals | Dynamic |
|  | Pasture-meals | Number of meals a pastureland cell owns | 0 – 1000; meals | Dynamic |
|  | meals | Number of meals any cell owns | 0 – 1000; meals | Dynamic |
|  | connectivity | Count of wildland cells neighboring an individual cell that are wildland | 0 – 8; wildland neighbors | Static |
|  | interior | If a wildland cell is surrounded by wildland cells | 0 or 1 | Static |
|  | edge | If a wildland cell is not entirely surrounded by wildland cells | 0 or 1 | Static |
|  | Fragment-number | The wildland fragment a cell belongs to | 1 – 9; fragment ID | Static |
|  | Possible? | If a cell is eligible to become a wildland cell during initialization | True/false | Dynamic |
|  | Habitat? | Designates wildland cells during initialization | True/false | Dynamic |

***Process overview and scheduling***

Prior to model initialization, users can choose the percentage of the landscape that is wildland and the number of fragments. Users select a livestock grazing treatment: *free roaming*, *pasture-limited*, or *seasonal grazing.* They can also adjust the number of wolf-, livestock-, wild prey-, and farm-agents on the landscape, turn off or on both the wild prey and livestock fear of wolves and the wolves’ fear of farms, and independently adjust the elasticity of the livestock herds and the wolf pack.

To initialize the model, each cell is randomly assigned number of “meals” for herbivores (wild prey- and livestock-agents), ranging from 1 – 1000. These meals are then delineated as either “wildland meals” or “pastureland meals,” depending on the designation of the cell. This meal availability is designed to replicate randomness in vegetation growth across the landscape according to the availability of nutrients, sunlight, water, etc. (Toombs et al. 2010; Briske 2017). The number of meals is not replenished over the course of a simulation run, resulting in a landscape that gradually degrades with each time step. This mimics the natural depletion that occurs over the course of one year in a grazing landscape, beginning with spring “green up” and concluding at the end of winter (Pettorelli et al. 2005).

Following initialization, the wolf pack is placed together on a single wildland fragment, the wild prey-agents are distributed randomly across the wildland fragments, farm-agents are distributed randomly across the pastureland cells (but cannot be within a ten-cell radius of one another), and livestock-agents are placed in their herds either at their farms (under *free roaming* and *pasture-limited* grazing treatments) or on a wildland fragment (under the *seasonal grazing* treatment).

Agent movements are not simultaneous: at the start of each time step, the wolf-agents perform their set of sub-models, followed by the wild prey-agents, with the livestock-agents moving last. At the start of each time step, the wolf pack leader follows the “fear-farms” sub-model, taking the appropriate action according to whether they find a farm-agent within a two-cell radius of their current location. After completing this process, the pack leader performs their movement hunting process (sub-models ‘hunt,’ ‘eat-elk,’ and ‘eat-cows’). Once the pack leader has finished their set of actions, each non-pack leader wolf engages in the ‘follow-pack-leader’ sub-model, whereby they assess the distance between themselves and the pack leader. If this distance is greater than the ‘pack-elasticity’ value set during initialization, the non-leader agent moves back toward the pack leader. If the non-leader agent is within the elasticity distance, they proceed with the ‘hunt,’ ‘eat-elk,’ and ‘eat-cows’ sub-models.

After the wolf-agents have completed their movement-hunting processes, the wild prey-agents engage in their movement-feeding routine. This process begins with each wild prey-agent following the ‘elk-fear-wolves’ sub-model. Then, the wild prey-agent assesses the number of meals available at each neighboring cell, regardless of its designation as pastureland or wildland. The wild prey-agent moves to the neighboring cell with the greatest number of available meals, acting to maximize their best interest. If an agent is on a cell surrounded by other cells in which all meals are depleted—i.e., there is no neighboring cell with an available, desirable meal—the agent randomly selects and moves to a cell within a two-cell radius of its current location. This process ensures than no wild prey-agent ends up stranded in one location. After the wild prey-agent has completed their movement process, they then follow the ‘eat-food’ sub-model.

The livestock-agents complete their movement-feeding routine last. This process varies according to each livestock grazing treatment. The scheduling process for each treatment is detailed below.

A diagram of a wild-prey

Description automatically generated

***Figure 1.*** *An overview of model processes from initialization to the beginning of each individual livestock grazing treatment.*

*Free roaming livestock*

The herd-leader agents first conduct the ‘cows-fear-wolves’ sub-model before beginning their movement-feeding routine. After completing this sub-model, each herd leader assesses the number of meals available at each neighboring cell, regardless of its designation as pastureland or wildland. The herd-leader agent moves to the neighboring cell with the greatest number of available meals, acting to maximize their best interest. They then follow the ‘graze-all’ sub-model. If the herd-leader agent finds itself on a cell surrounded by cells in which all the meals have been consumed (i.e., meal values of zero), the agent will randomly select and move to a cell within a two-cell radius of its current location. This process ensures that no herd-leader agent ends up stranded in one location. If the livestock-agent is not a herd leader, they perform their actions once the herd leaders have completed their processes. The non-herd leader agents engage in the ‘follow-herd-leader-all’ sub-model, in which they follow the same set of processes as the herd-leader agent after first assessing the distance between themselves and their herd leader. If this distance is greater than the ‘herd-elasticity’ value set during initialization, the non-leader moves toward their herd leader before engaging in the movement-feeding routine detailed for herd leaders above.

A diagram of a business flowchart

Description automatically generated

***Figure 2.*** *Model processes for the free roaming livestock grazing treatment.*

*Pasture-limited livestock*

The livestock-agents in this treatment follow the same set of processes as those in the *free roaming* treatment but are restricted to moving across and consuming meals from the pastureland cells. The herd leaders perform the ‘cows-fear-wolves’ sub-model, before moving to the neighboring pastureland cell with the greatest number of available meals. They then follow the ‘graze-pasture’ sub-model. If the herd-leader agent finds itself on a pastureland cell surrounded by cells in which all the meals have been consumed (i.e., meal values of zero), the agent will randomly select and move to a pastureland cell within a two-cell radius of its current location. This process ensures than no herd-leader agent ends up stranded in one location. If the livestock-agent is not a herd leader, they perform their actions once the herd leaders have completed their processes. The non-herd leader agents engage in the ‘follow-herd-leader-pasture’ sub-model, in which they follow the same set of processes as the herd-leader agent after first assessing the distance between themselves and their herd leader. If this distance is greater than the ‘herd-elasticity’ value set during initialization, the non-leader moves toward their herd leader before engaging in the movement-feeding routine detailed for herd leaders above.

A diagram of a wolf

Description automatically generated

***Figure 3.*** *Model processes for the pasture-limited livestock grazing treatment.*

*Seasonal grazing livestock*

The livestock-agents in this treatment follow the same set of processes as those in the *free roaming* and *pasture limited* treatments but are restricted to moving across and consuming meals from a wildland fragment for time steps 0 – 182 and pastureland cells for time steps 183 – 365. The herd leaders perform the ‘cows-fear-wolves’ sub-model before moving to the neighboring cell with the greatest number of available meals—the type of cell the herd leader is eligible to move to is dependent upon what time step the model is at. They then follow either the ‘graze-habitat’ or ‘graze-pasture’ sub-model. Much like in the other two livestock grazing treatments, if the herd-leader agent finds itself on a cell surrounded by cells in which all the meals have been consumed, the herd leader will randomly select and move to a cell within a two-cell radius of their current location that matches the habitat designation they are allowed to move within at that time step. This process ensures than no herd-leader agent ends up stranded in one location. If the livestock-agent is not a herd leader, they perform their actions once the herd leaders have completed their processes. The non-herd leader agents engage in the ‘follow-herd-leader-herded’ sub-model, under which they follow the same set of processes as the herd-leader agent after first assessing the distance between themselves and their herd leader. If this distance is greater than the ‘herd-elasticity’ value set during initialization, the non-leader moves toward their herd leader before engaging in the movement-feeding routine.

A diagram of a diagram

Description automatically generated with medium confidence

***Figure 4.*** *Model processes for the seasonal grazing livestock grazing treatment.*

After the movement processes have been completed, the ‘time-since-meal’ counter increases by one, tracking how long it has been since the wolf pack made a kill. Then, the model advances by one time step and the process begins again. The model runs for 365 time steps.

***Design concepts***

*Basic Principles*

Predator-prey interactions are necessary for the persistence of species like gray wolves and are a fundamental aspect of carnivore ecology. The characteristics of these interactions can vary according to landscape and species assemblage. In areas of the Western United States where gray wolves co-occur with domesticated livestock, the two groups share some degree of interaction—most notably in the form of livestock depredations. These instances can occur across a wide range of landscapes that vary in their composition, land use designation, and livestock herding practices. Though we have a thorough understanding of operation- or pack-specific characteristics that may exacerbate these instances (presence of bone piles or carcasses, calving practices, learned pack behavior, etc.), there may be landscape-scale processes at play that intersect with these local-level variables to exacerbate or alleviate instances of depredation. However, evaluating the emergence of patterns according to landscape-scale variation in a real-world setting is challenging due to the wealth of data and diversity of study systems this work would require. This model enables variation in landscape characteristics with the implementation of other basic principles such as hunting and foraging processes, fear responses, and herding or packing behavior as sub-models. This model examines how landscape composition affects instances of livestock predation by considering the intersection of movement and behavioral processes of multiple species with landscape-scale patterns in connectivity and habitat extent.

*Emergence*

As wildland connectivity and availability increase, the rate at which wolves prey upon livestock declines, regardless of how livestock-agents are moved across the landscape. These trends largely appear due to increased wolf access to wild prey-agents. On landscapes with limited connectivity, trends in livestock and wild prey consumption break down, reducing predictability of risky spaces. Furthermore, when livestock graze seasonally on wildlands, they experience greater amounts of predation on wildland cells than would be expected at random—though overall losses of *seasonal grazing* livestock are not significantly higher than the other two grazing treatments. This finding indicates the high level of risk involved in utilizing wildlands for seasonal livestock grazing.

*Adaptation*

If the livestock and wild prey fear sub-model is turned on, when a wolf-agent comes within a one cell radius of either agent type, they adapt their movement pattern, moving in the opposite direction to avoid being eaten (Miller & Schmitz 2019).

When the wolf fear sub-model is turned on, if a wolf-agent comes within a two-cell radius of a farm-agent, the wolf-agent adapts their movement pattern, moving in the opposite direction out of fear of humans (Theuerkauf 2009; Carricondo-Sanchez et al. 2020).

If a livestock or wild prey-agent finds themselves on a cell surrounded by cells with zero available meals, they will engage in a random walk, moving two cells in a random direction before attempting to graze again.

*Objectives*

None.

*Learning*

None.

*Prediction*

None.

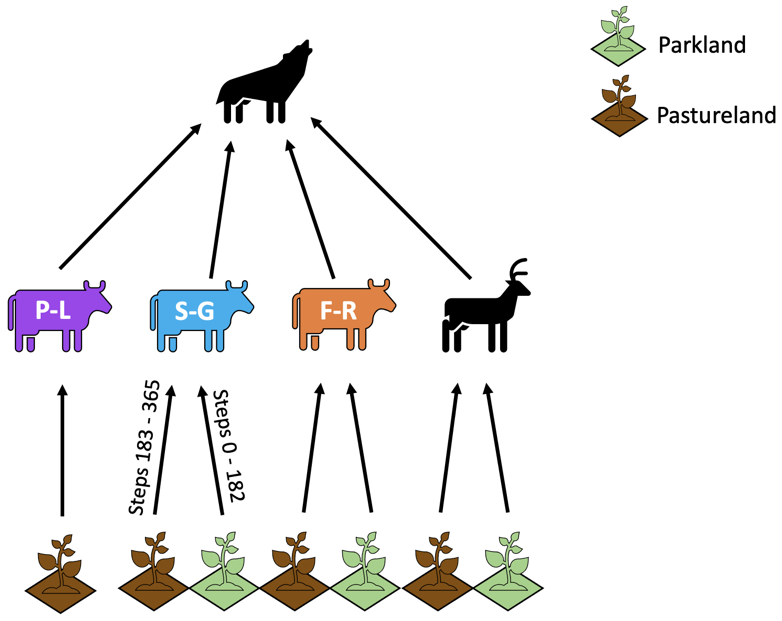
*Sensing*

When the fear sub-models are running, the wild prey and livestock-agents can sense wolf-agents, and the wolves can sense farm-agents. In these scenarios, this “sensing” drives the affected agent to move away from the feared agent. Conversely, when wolves are hunting prey, they can sense the presence of the prey within a certain radius and move toward them. These behaviors represent the ability of prey species to detect and flee from predators, the tendency of large carnivores like wolves to avoid human settlements, and the ability of a predatory species like the gray wolf to find and hunt their prey (Carricondo-Sanchez et al. 2020).

When engaging in the movement-feeding routine, the wild prey and livestock-agents can sense the number of meals present at each accessible neighboring cell, opting to move to the neighboring cell with the greatest number of available meals. Furthermore, when engaging in their movement-feeding pattern, wild prey and livestock-agents can sense when all the neighboring cells have meal values of zero. When this occurs, the affected agent engages in a random walk and moves two cells instead of one, so they don’t end up stranded in a depleted area. It is assumed that the wild prey and livestock-agents are capable of assessing their surroundings, identifying, and moving toward preferred forage.

*Interaction*

The livestock and wild prey-agents interact with the cells directly by removing meals through consumption. Wolf-agents interact with the livestock and wild prey-agents indirectly through fear effects, and directly through consumption. Wolf-agents also interact indirectly with the farm-agents, whom they avoid by not approaching closer than two cells.



***Figure 5.*** *Food web showing the direct interactions occurring within the model. Wild prey- and livestock-agents consume “meals” from wildland and pastureland cells, with livestock consumption dictated by which grazing treatment is applied to each run. Wolf-agents consume both wild prey- and livestock-agents. Each colored cow represents a specific livestock grazing practice: pasture-limited, seasonal grazing, or free roaming.*

*Stochasticity*

Initial meal values across all cells are randomly assigned values ranging from 1 – 1000. The initial placement of wild prey-agents on wildland cells is random, as is the location of farm-agents on pastureland—so long as they are more than ten cells away from the next closest farm. The wolf pack is assigned first to a random wildland fragment, then a random cell within that fragment. In both the *free roaming* and *pasture-limited* livestock treatments, the livestock-agents begin at their associated farm-agent. Under the *seasonal grazing* treatment, the livestock herds are first randomly assigned to a wildland fragment, then to a cell within that fragment.

If it has been fewer than two time steps since the wolf pack made a kill during the movement-hunting process or if the wolf-agents do not find any prey during their movement-hunting process, they will engage in a random walk, emulating stochastic movement patterns. Similarly, as part of the forage-searching routine when neighboring cells all have meal values of zero, the wild prey and livestock-agents will engage in a random movement to find cells with greater meal values.

*Collectives*

The wolf-agents move in a pack with a variable level of elasticity that determines how far away from the pack leader any non-leader agents can move without returning to the pack leader before going about any of the standard movement processes (fear of farms, movement-hunting, etc.) As a result, the movement of the pack leader drives the movement patterns of the entire pack. The livestock-agents move in herds with a variable level of elasticity that determines how far away from the herd leader any non-leader agents can be without returning to their herd leader before going about any of the standard movement processes (movement-feeding, fear of wolves, forage-searching, etc.) Much like with the wolf-agents, the movements of the individual herd leaders drive the movement patterns of each individual herd.

*Observation*

We collected several pieces of information at the end of each simulation run to better understand the emergence of trends in wolf predation rates, locations, and prey type: (1) a count of the number of livestock-agents killed by wolves, (2) a count of the wild prey-agents killed by wolves, (3) whether each kill (livestock or wild prey) occurred on a wildland or pastureland cell, and (4) if a kill did occur on a wildland cell, whether that particular cell was an edge or interior cell.

***Initialization***

To build the park- and pastureland landscape for the simulation, the model first counts the total number of patches (10,000). Then, the model sets the number of patches that should be labeled as wildland. To do so, the ‘patch-availability’ value selected by the user is divided by 100 and multiplied by the total number of patches (e.g., for a landscape with a ‘patch-availability’ of 25%, the model would calculate 0.25 \* 10,000 = 2,500 wildland patches). All cells are designated as pastureland with the potential to be turned into wildland as the model initializes. Then, the model moves through a series of sub-models, beginning with ‘setup-patches,’ detailed below.

Setup-patches: this sub-model seeds the initial cells that will ultimately grow outward and become the wildland fragments. The model picks a random cell that is both not green (the landscape hasn’t been assigned any colors at this point, so no cells are green), nor are any of the neighboring eight cells green. This cell is turned green, designated as wildland, and assigned a fragment number. Once these steps have been completed, the process repeats until the number of green cells on the landscape matches the ‘number-fragments’ input by the user at the beginning of the initialization. Because the selection of cells is random, the initial wildland seed cells are different in every simulation.

Grow-patches: the cells designated as wildland in the ‘setup-patches’ sub-model are expanded outward in this model and grown to their full size. So long as the number of patches that are green is less than the number of patches that should be labeled as wildland (2,500 for a ‘patch-availability’ setting of 25%), the sub-model repeats a loop. First, it selects one of the patches already designated as wildland and asks the surrounding patches to also become wildland, so long as they are not within four cells of a different fragment—this command retains a corridor at least four pastureland cells wide between the fragments. This process is repeated until the total number of wildland cells is met (i.e., in a 25% ‘patch-availability’ landscape, 2,500 cells have been turned to wildland). The number of wildland cells is summed across fragments in each simulation, ensuring the correct percentage of wildland is available while allowing fragments to vary in size (i.e., in a landscape with 25% wildland availability, fragments could be 2,000, 400, and 100 cells in size, summing to a total of 2,500 wildland cells on the landscape).The sub-model then randomly assigns all of the cells a meal value between one and 1,000. Meals are designated as ‘patch-meals’ for wildland cells, or ‘pasture-meals’ for pastureland cells. Then, the ‘set-patch-color’ sub-model is called. The stochasticity introduced in the patch growth portion of this sub-model, along with the random meal allocation, ensures that both the composition of the landscape and the distribution of nutrients are unique to each simulation.

Set-patch-color: If a cell is designated as wildland, it is turned green. If a cell is designated as pastureland, it is brown.

Connect: assesses the connectivity of wildland cells with other wildland cells. If a wildland cell is surrounded completely (all eight neighbors) by other wildland cells, it is marked as an interior cell. Wildland cells that are not entirely surrounded by wildland are marked as edge.

Setup-wolves: the pack leader is created first and placed on a random wildland cell (see ‘pick-wolf-patch’ sub-model). The other five wolves are hatched from this wolf. The number of wolves can be adjusted by the user prior to initialization.

Pick-wolf-patch: a random wildland fragment number is selected, and the wolf pack leader is placed on a random cell in that fragment.

Setup-elk: 480 wild prey-agents are randomly distributed across wildland cells. The number of wild prey-agents can be altered by the user prior to initialization.

Setup-farms: ten farm-agents are created on pastureland cells and cannot be placed within ten cells of another farm-agent. Each farm-agent will first hatch their herd leader livestock-agent, who identifies the farm they were hatched at as ‘my-farm.’ The remaining 44 individuals in each herd are hatched, designate the farm they were hatched at as ‘my-farm,’ and identify their herd leader. The number of farms and the number of individuals in a herd can be adjusted by the user prior to initialization.

*Input*

To begin the initialization process, users first must select the number of fragments they would like created on the landscape (‘number-fragments’, 0 – 20), the extent of the landscape they would like to be wildland (0 – 100% in increments of 25, ‘patch-availability’), and the livestock grazing treatment they would like to run (‘cattle-treatment’; ‘cattle-everywhere,’ ‘cattle-herded,’ ‘cattle-pasture’). The user can also alter the number of farm-, wolf-, wild prey-, or livestock-agents, turn on or off the livestock and prey agents’ fear of wolves or the wolves’ fear of farms, and adjust the elasticity of both the livestock herds and the wolf pack.

*Sub-models*

Eat-elk: when the wolf-agent is hunting, if they catch a wild prey-agent during the hunt sub-model, they engage in this process. If it has been more than two time-steps since the pack has consumed prey, the wolf will kill the wild prey-agent, emulating natural predation rates for a wolf pack made up of six individuals (see Table S1 for parameter values and sources).

Eat-cows: When the wolf-agent is hunting, if they catch a livestock-agent during the hunt sub-model, they engage in this process. If it has been more than two time-steps since the pack has consumed prey, the wolf will kill the livestock-agent, emulating natural predation rates for a wolf pack made up of six individuals (see Table S1 for parameter value and sources). If the livestock-agent consumed by the wolves was the leader of one of the herds, the closest livestock-agent that belongs to the same herd as the deceased leader becomes the new herd leader.

Hunt: the wolf-agents identify both the wild prey and the livestock-agents as possible food sources, representing the breadth of diet seen in wild wolf packs (Morehouse & Boyce 2011; Newsome et al. 2016). The wolves engage in the hunting-movement routine by assessing the cells within a three-cell radius for the presence of prey agents at each time step. If there is a prey agent within this radius and it has been more than two time steps since the pack has eaten, the wolf-agent adjusts their heading toward the prey agent, moving forward two cells. If this movement lands the wolf on the same cells as the prey agent, the prey agent dies and is consumed by the wolf. If the wolf-agent does not find any prey agents within a three-cell radius, or if they find prey within a three-cell radius but it has been two time steps or less since they had a meal, they engage in a random walk, picking a random number from one to 360, adjusting their header by the number of degrees they have selected and moving two cells in that direction. This represents the average daily movement of an individual wolf (see Table S1).

Fear-farms: Gray wolf-agent movement across the landscape is informed by fear effects and wolf avoidance of humans in addition to prey drive (Theuerkauf 2009; Carricondo-Sanchez et al. 2020). Prior to assessing nearby cells for prey agents, the wolf-agent examines all cells within a two-cell radius, checking for farms. If there are no farm-agents within this radius, the wolf-agent proceeds with a standard hunting-movement process. If there is a farm-agent within a two-cell radius, the wolf turns 180° and moves one cell in the opposite direction of the farm. The wolf-agent then proceeds with the hunting-movement routine.

Follow-pack-leader: If the wolf-agent is not the pack leader, they first assess the distance between themselves and the pack leader. If the pack leader is more than four cells away from them, the non-pack-leader agent adjusts their heading and moves toward the pack leader agent. If the non-pack-leader agent is within four cells of the pack leader, they follow the same movement-hunting routine as the pack leader.

Elk-fear-wolves: The movement of wild prey-agents is, in part, shaped by the presence of wolves (Miller & Schmitz 2019). At the start of each time step, wild prey-agents assess all cells within a one-cell radius of their current location for the presence of wolves. This model assumes perfect detection of wolves by the wild prey-agents. If no wolves are present, they begin a standard movement-feeding routine (the ‘eat-food’ sub-model). If wolves are present within a one-cell radius of their location, the wild prey-agent turns 180° and moves one cell in the opposite direction. The wild prey-agent then resumes its standard movement-feeding routine.

Eat-food: Once a wild prey-agent selects a cell and moves to it, the agent consumes one meal from the chosen cell, reducing the number of meals available at that location by one. This routine of choosing the best neighboring , moving to it, and eating a single meal is repeated by each wild prey-agent at each time step.

Herding-pattern: In the *seasonal grazing* treatment, livestock move within wildland fragments for time steps 0 – 182 of the simulation and within pastureland for time steps 183 – 365. This treatment is designed to emulate a grazing practice that is employed across large areas of the West, where many livestock owners move their livestock to grazing allotments on public lands for a portion of the year (Fleischner 1994). Grazing allotment time frames vary: some permits allow ranchers to graze livestock on an allotment year-round, while some are only for a few months out of the year. Many livestock owners place their herds on allotments in the spring, as forage availability begins to increase, leaving them to graze until the fall before moving them back to pasture (Huntsinger et al. 2010). This process is what the *seasonal grazing* treatment seeks to mimic. To replicate the use of grazing allotments in the *seasonal grazing* treatment, all herds begin on a randomly selected wildland fragment at time step zero. At each subsequent time step, each herd leader engages in the movement-feeding pattern, constrained to moving within the wildland cells comprising the fragment they are on. At time step 183, herd leader agents move back to their farm, and the non-herd-leaders move with them. Livestock herds then follow the same process as in the *pasture-limited* treatment, restricted to pastureland through time step 365. Across all time steps, livestock-agents engage in forage-searching movement—limited first to wildland cells for steps 0 – 182, and then to pastureland cells for steps 183 – 365.

Follow-herd-leader-all: Non-herd-leader livestock-agents under the *free roaming* treatment first assess the distance between themselves and the herd leader, moving to their leader if more than a four-cell distance away, and engaging in the movement-feeding pattern if not.

Follow-herd-leader-pasture: Non-herd-leader livestock-agents under the *pasture-limited* treatment first assess the distance between themselves and the herd leader, moving to their leader if more than a four-cell distance away, and engaging in the movement-feeding pattern on pastureland cells if not.

Follow-herd-leader-herded: Other livestock-agents first assess the distance between themselves and the herd leader, moving to their leader if more than a four-cell distance away, and engaging in the movement-feeding pattern on wildland cells for time steps 0 – 182, and pastureland cells for time steps 183 – 365 if not.

Cows-fear-wolves: Recognizing that livestock, like wild prey, may engage in anti-predator foraging and movement, livestock-agent foraging movement is also determined by the presence of wolves on the landscape (Kluever et al. 2008; Laporte et al. 2010).When determining where to move at any given time step, livestock-agents first assess all cells within a one-cell radius, looking for wolves. When the model is initialized, all livestock-agents have a wolf-encounter tally of zero, emulating naivety (Laporte et al. 2010). After a livestock-agent finds a wolf-agent within a one-cell radius of themselves, their wolf-encounter number increases to one. Any livestock-agent with a wolf-encounter value of one or higher fears the wolf-agents. This model assumes perfect detection of wolves by the livestock-agents. Should a wolf be within a one-cell radius of their location when engaging in this sub-model, the livestock-agent will turn 180° and move one cell in the opposite direction. The livestock-agent then proceeds with the movement-feeding pattern stipulated by their role and the grazing treatment applied to the current simulation. If no wolves are present, the livestock-agents proceed with the movement-feeding routine dictated by their role as either a herd leader or non-herd-leader, and the grazing treatment for that simulation.

Graze-all: Once a livestock-agent under the *free roaming* treatment selects a cell and moves to it under the move-cows sub-model, it consumes one meal from the chosen cell, reducing the number of meals available at that location by one. This routine of choosing the best neighboring cell, moving to it, and eating a single meal is repeated by each livestock-agent at each time step.

Graze-pasture: Once a livestock-agent under the *pasture limited* treatment or the *seasonal grazing* treatment during time steps 183 - 365 selects a cell and moves to it under the ‘move-cows’ sub-model, it consumes one meal from the chosen cell, reducing the number of meals available at that location by one. This routine of choosing the best neighboring cell, moving to it, and eating a single meal is repeated by each livestock-agent at each time step.

Graze-habitat: Once a livestock-agent under the *seasonal grazing* treatment time during steps 0 -182 selects a cell and moves to it under the ‘move-cows’ sub-model, it consumes one meal from the chosen cell, reducing the number of meals available at that location by one. This routine of choosing the best neighboring cell, moving to it, and eating a single meal is repeated by each livestock-agent at each time step.

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