

Evaluating scenarios using an agent-based model for pheasant populations and biomass harvest strategies

A Thesis Presented for the
Master of Science
Degree
The University of Tennessee, Knoxville

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August 2019

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To every one of my teachers and mentors over the years who saw something in me that I didn't see myself.

Thank you for encouraging me to keep going; I would be nothing without your constant guidance.

And to Maushi Aaji, who left us too soon.

Acknowledgements

First and foremost I would like to thank my committee: Drs. Suzanne Lenhart, Yetta Jager, and Mona Papes. I can't even begin to describe the impact your mentorship has had on my life. Suzanne, thank you for taking me under your wing and guiding me through my graduate education. I would be very lost without you. Yetta, there are too many things to thank you for that I don't know if I'll ever be able to fully articulate them all. Thank you for taking a chance on a recent college grad all those years ago. My life wouldn't be the same if it wasn't for you. And Mona, thank you so much for your relentless kindness and positivity. You always manage to bring a smile to my face and make me feel like I can accomplish anything. Thank you all for being such wonderful, diverse role models of what it can look like to be a woman in science — I hope to have half the impact on other girls someday.

I'd also like to thank Pam Armentrout, goddess of the math department, who without, none of this would truly be possible. Thanks to all my graduate student friends who supported me and commiserated with me as we did our best to make it through; special shout-out to my favorite people to pull an all-nighter with, Alex and Becca. I'd especially like to thank Shelby Scott for her amazing introduction to NetLogo, I would be so lost without you! Thanks to Cleo and Mae, you don't realize it, but you always brighten my day. Of course, big thanks to my coven: Riley, Mari, Sietske, Nie, Dipa, Daniele, and Millie — you ladies give me life, pick me up, and make me feel oh-so-powerful.

And finally, to my parents and partner Reed. Mom and dad, you have been with me since day one and are the reason for everything I do. I have no idea what I did in a previous life to be so lucky to have you both, but all I know is that you are truly the best parents in the world. You two are my best friends and my constant inspiration — thank you. To my darling Reed, I'm so glad we found each other. Thank you for being my human and choosing me to share your life with. I'm so proud of all that we've been able to create together and I can't wait to see what life has in store for us.

Abstract

Ring-necked pheasants (*Phasianus colchicus*), while a non-native species in North America, is a popular game species. Many mid-western states, including Iowa, depend on the revenue that hunting tourism generates. Thus, there are programs to ensure pheasant populations do not decline, the most ubiquitous being Conservation Reserve Programs (CRP). By enrolling land in CRP, farmers remove that land from traditional agricultural production and receive rental payment. Additionally, farmers plant crops that simulate pheasant habitat, which can be harvested as biomass feedstock. In this study, we build a spatially-explicit agent-based model (ABM) to simulate dynamics associated with pheasants, hunters, and tractors on a typical Iowa field with CRP land. We evaluate the model's ability to realistically represent dynamics of agents and their interactions. The ABM simulates pheasant population trends over time, under varied sex-ratio probabilities, and exhibits reasonable habitat-use by pheasants. We compare two scenarios (S2, S3) that differ in spatial and temporal rules for tractors and hunters to investigate the effect such constraints have on pheasant populations and harvested biomass. S3 (harvest outward spiral, mow once between August 1 - 15) had approximately 10,000 tons/km² more biomass harvested than S2 (harvest inward spiral, two-cut system), though a portion of this difference can be attributed to model assumptions and must be further investigated. However, double the number of roosters were killed by hunters in S2 (strip hunting, 93 day season) compared with S3 (radial hunting, 42 day season). Proportionally, roosters were killed at the same rate, indicating that spatial constraints on hunters have less impact on the number of roosters killed compared to length of the hunting season. Accidental rooster death by tractor was also tracked in each scenario (S2 - 220, S3 - 52), and these deaths may be lower in S3 because tractors are mowing after hens have finished using the area to rear broods. In comparison, mowing occurs in S2 while hens are nesting. Overall, these results are promising and planned future work should provide valuable insight into the effect spatiotemporal harvesting constraints have on pheasants and biomass.

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1 Introduction

Often, agricultural practices and conversion to agricultural landscapes have detrimental effects on wildlife. Planting traditional row crops not only destroy their natural habitat, but can also cause habitat fragmentation. Robust biodiversity in agricultural landscapes has high ecological value, however it can also provide economic value through hunting. This value is revealed through hunters buying hunting licenses, paying farmers to hunt on their lands, and comprising a large sector of the tourist economy in many mid-western states. One such species that generates a lot of such interest is the ring-necked pheasant (*Phasianus colchicus*).

Although native to Asia, pheasants have been widely introduced around the world and are one of the most well-known, and ancient game birds. Thanks in part to its popularity as a game bird, there are various governmental programs, such as the US Conservation Reserve Program (CRP) [13, 36, 37, 41], that seek to recover and maintain pheasant populations. One such CRP program in Iowa, referred to as CRP SAFE, has farmers grow perennial grasses rather than traditional row crops in parts of their land, in order to simulate pheasant habitat. It has been demonstrated that pheasant populations respond positively when previously agricultural land transitions to CRP land, and interspersed local grassland patches within landscapes containing small grains and row crop agriculture is a critical element in maintaining ring-necked pheasant populations [28]. Avian nesting habitat is severely limited in agriculturally dominated landscapes though rowcrops, especially corn, do provide high quality food and cover, at least until the field is disturbed by harvesting practices. CRP plans can be successful in assuaging pheasant’s habitat needs because the grass-like habitat created by small grains and perennial grasses may significantly increase breeding opportunities for pheasants [28].

An added benefit and further economic incentive to landowners to participate in this program, is that the acres of perennial grasses planted for CRP can be harvested as biomass. This is favorable for birds because these grasses do not have to be harvested immediately. Thus, it is possible to avoid harvesting during the nesting season for most wildlife species, including pheasants. It has been suggested that leaving standing biomass over winter provides important wildlife cover and seed forage, but this can also result in degradation of material [20]. Hence, there are trade-offs between harvesting pheasants and biomass.

The objectives of this study are three-fold: (1) create a spatially-explicit model that appropriately represents pheasant dynamics in an agricultural setting and realistically represent the interactions between pheasants, the landscape, hunters, and tractors in the model, (2) compare modeled results with observed data and evaluate model performance in comparison to other pheasant models, and (3) run two harvesting scenarios in the model and evaluate their performance in terms of harvested biomass yield, killed roosters,

and regular cyclic fluctuations of the pheasant population under these various management options. We evaluate the ABM's performance in a baseline analysis, construct five spatiotemporal harvesting scenarios of both tractors and hunters, and finally evaluate two of those five scenarios.

2 Background

This section will provide further information on the core topics of this project: ring-necked pheasants, Conservation Reserve Programs, spatially-explicit agent-based models, spatiotemporal harvest planning, and perennial biomass feedstocks.

2.1 Ring-necked Pheasant Life History

Ring-necked pheasant life history stages and processes form the basis of the modeling framework [2, 5, 7, 11, 14, 17, 18, 21, 23, 26, 27, 32, 40, 47, 51, 53]. By extracting information on movements between seasons, breeding behavior, chick production and growth, brood rearing, age- and sex-specific behaviors, as well as seasonal, age, and sex differences in survivorship, the model can act as a facsimile of natural pheasant dynamics. A generalized conceptual model of ring-necked pheasant life history is presented in Figure 1.

This figure shows movements between seasonal habitats and the important activities that occur in those habitats. Three seasons are shown: spring (March - late June, representing the breeding season where lekking, mating, nesting, and brood rearing occur), summer (June - mid-September), and winter (December - late February). Autumn (mid September - December) is a transition period when pheasants move from summer to winter habitat. Males and females differ in their use of seasonal habitats, as described below. Seasonal habitat requirements are also discussed.

2.1.1 Spring

Ring-necked pheasants breed during the spring season. In March, males begin to establish crowing grounds. These are areas where they lek, or display various courtship behaviors in an attempt to attract females. Rarely do these displays result in violent confrontations, though they can occur. Males mate with any receptive hen that enters their territory. Harems can get as large as twelve hens.

Nesting can begin as early as March in southern Iowa, but egg laying usually begins in mid to late April, peak incubation occurs in May, and peak hatch is usually early to mid June [14]. Only the hen takes part in nesting and incubation. After constructing a nest, the hen lays 6 to 15 eggs, often 10 to 12 [5]. Hens lay one egg per day until the clutch is complete, and then incubation begins. Ring-necked pheasant hens often renest after a clutch is destroyed. Hens will continue nesting attempts until a clutch is successfully hatched, a clutch is lost late in incubation, or she is no longer able to produce eggs that season [51]. Hens can initiate as many as 5 nests in a single season [42]. The average number of eggs laid per clutch decreases by one or more with each successive attempted renest [53]. Hens incubate eggs for 23 to 25 days [5]. Hens will only have one brood per breeding season, though because of renesting, it is possible for a hen to have a brood of

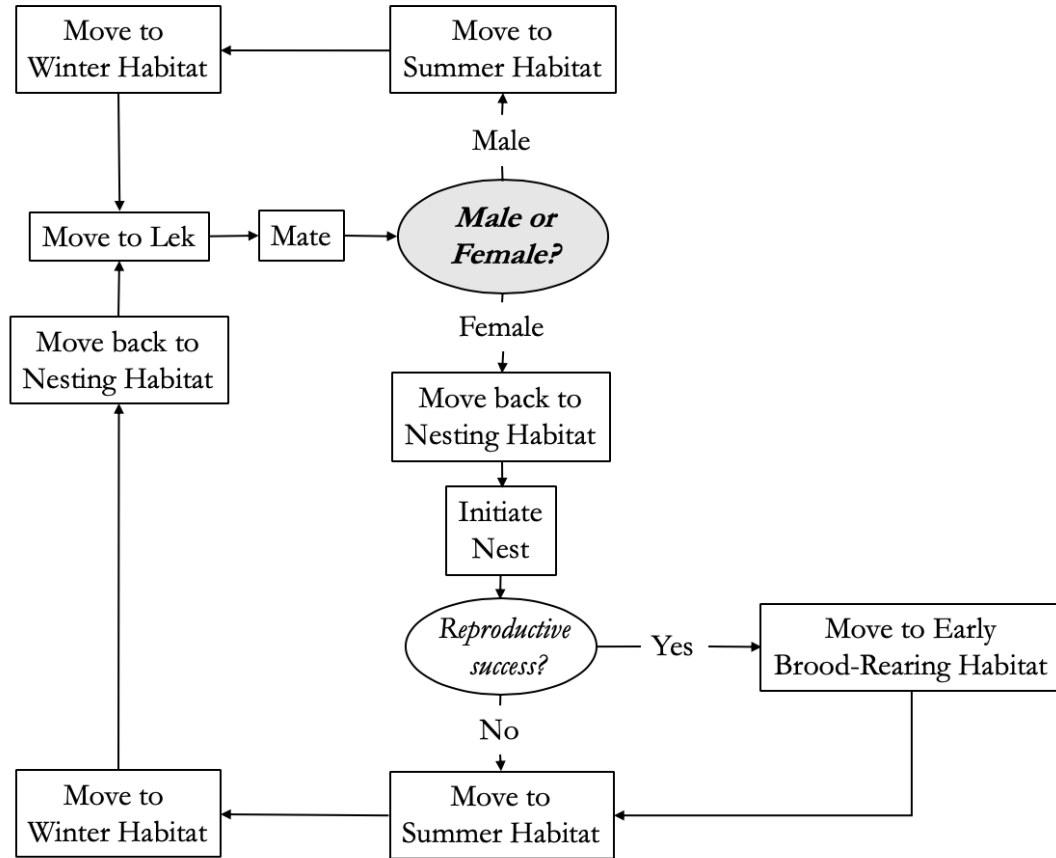


Figure 1: **Conceptual model of ring-necked pheasant life history** - Juveniles stay with their mother until moving to winter habitat

different ages. These details are important as they are represented in the ABM when pheasants go through their reproductive process.

2.1.2 Summer and Autumn

Young chicks can leave the nest and follow their mother within a few hours of hatching. Young chicks can make short flights at 12-14 days of age and resemble adults by 16 weeks of age [14]. Even though young resemble adults relatively fast, they will stay with their mother for 3 months after hatching and during this time the mother will still display protective behavior over her young. Male pheasants will occasionally spend time with broods of young, but play no role in rearing chicks - this is left completely up to the mother. Hens will take their broods to good insect hunting areas and warn chicks of impending danger. Mortality of young chicks is high. The mortality between hatching and 2 weeks of age may be as high as 25% and may increase to almost 50% by 9 weeks of age [42]. The main causes of chick loss are chilling rain or hail storms, predation, road traffic, and farming operations [53].

2.1.3 Winter

By winter, chicks no longer rely on their mothers for food and protection, and broods break up. All pheasants, both males and females, seek out appropriate winter cover in which to spend the winter. This is also the only season in which pheasants will associate with other members of the same-sex; pheasants flock by sex as they search for winter habitat [51]. Suitable winter cover is close to a winter food source because pheasants will forage only short distances during this season. Mortality does not increase during winter, since pheasants can survive bouts of freezing temperatures, as long as they are able to consume enough high caloric food to keep body temperatures high [53].

2.1.4 Seasonal Habitat Requirements

Ring-necked pheasant habitat is associated with areas of high soil fertility where agricultural crops and other vegetation provide the basic food and cover requirements [5]. Pheasants occupy crop fields of corn, sorghum, oats, wheat and barley stubble, unmowed wild haylands, native grasslands of big and little grasses with a healthy forb component, grassy roadside ditches and field drainage channels, dense vegetation growing along overgrown fence-rows, windbreaks, shelter-belts, woodlots, and field corners. Table 1 provides a summary of the various habitat requirements of pheasants [18].

Table 1: **Ring-necked pheasant habitat requirements summary** - This table, from [18] details different habitat requirements by habitat components for pheasants

Habitat Component	Habitat Requirement
General	• Crop fields of corn, sorghum, oats, wheat, barley and other small grains • Wild haylands, big and little bluestem, Indiangrass, sideoats grama, switchgrass, native forbs • Dense vegetation growing along overgrown fence-rows, windbreaks, shelter-belts, roadside and field ditches, small woodlots, old fields, and grassy or shrubby odd areas and field corners
Food - young	• Insects: grasshoppers, crickets, potato beetles, caterpillars of gypsy moths and browntail moths, tent caterpillars, cutworms, and others
Food - adult	• Forb seeds: legumes, ragweeds, smartweed, crotons, burdocks, others • Cultivated crops: corn, milo, wheat, grain sorghum, barley oats, buckwheat, sunflowers • Mast: acorns, pine seeds, various berries • Insects: grasshoppers, crickets, potato beetles, caterpillars of gypsy moths and browntail moths, tent caterpillars, cutworms, and others
Cover - nesting	• Wheat stubble, winter wheat, undisturbed grasslands and pastures, unmowed native and alfalfa haylands, grassy field corners and odd areas, overgrown hedgerows and fence-rows • Alfalfa, vetch, sweet clover, and cool seas grasses and forbs providing residual cover and ground litter
Cover - brood reading	• Mix of grass and forbs providing movement of foraging chicks along the ground with overhead cover • Big and little bluestems, sideoats grama, switchgrass, tall and intermediate wheat grasses, smooth brome, wildrye, Indian grass, mixed grasses, and forbs
Continued on next page	

Table 1 – continued from previous page

Habitat Component	Habitat Requirement
Cover - winter	• Weedy fence-rows, dense, undisturbed grasslands, old fields • Weedy playa lake bottoms, cattail marshes • Low-growing evergreen/hardwood windbreaks and shelter-belts, low-growing grassy and shrubby habitats
Cover - roosting and escape	• Trees, tall shrubs, hedges, weedy field borders, ditch banks, and fence corners • Cattail marshes, brush heaps, briar patches, small farmland woodlots and thickets
Water	• Daily foods eaten provide an adequate amount of water
Interspersion	• Cropfields of corn, sorghum, oats, wheat, and barley stubble • Wild haylands, big and little bluestem, Indiangrass, sideoats grama, switchgrass, tall and intermediate wheat grasses, smooth brome, wildrye, alfalfa, vetch, sweet clover • Grassy roadsides, field borders, filter strips and ditch banks, cattail marshes, abandoned farmsteads, grass/shrub-mixed odd areas and field corners • Brush heaps, briar patches, small farmland woodlots, and travel corridors consisting of hedgerows, overgrown fence-rows, field borders, grassed waterways, windbreaks, and shelter-belts
Minimum habitat size	• 60.7 km²; however, daily activities of ring-necked pheasants are typically conducted on one square mile or less under optimal habitat conditions

2.1.5 Pheasant Models

Much literature, in an observed and simulated context, exists on ring-necked pheasant population responses to management practices [4, 28, 31] and pheasant population responses to disturbances [16, 32, 51], among others. However, modeled results illustrating the cyclical nature of pheasant populations are less common. Dr. William Clark of Iowa State University created the PHEASCAPE individual-based model to examine pheasant population dynamics over time [9]. The annual cycle and a 10 year simulation of pheasant population from PHEASCAPE are shown in Figure 2.

The top graph of Figure 2 shows the annual cycle of simulated pheasant populations. At the beginning of the year, the population is at some value and then slowly decreases until just before mid-spring when the population reaches the lowest value all year. As new chicks hatch, the population spikes; it spikes in a relatively short period of time because there is a short period in which hatching occurs. From the birth spike, the population will then gradually decrease as the year progresses. Overall, the population exhibits regular cyclic fluctuations. The bottom graph of the same figure shows the simulated pheasant population over 10 years. The most striking thing about this graph is the representation of the annual cycle of a pheasant population over such a long period. From this, it can be seen that simulated pheasant populations adhere, on the whole persistent, even with the boom and bust nature of their reproductive processes. This is a distinct pattern of pheasant populations dynamics [9].

2.2 Conservation Reserve Program

The Conservation Reserve Program (CRP) is a U.S. land conservation program where in exchange for a yearly rental payment, farmers enrolled in the program agree to remove environmentally sensitive land from agricultural production and switch from growing traditional row crops to prescribed plants that are meant to improve environmental health and quality. Originally a branch of the Soil Bank Program in the 1950s when the program was conceived, the Farm Bill of 1985 [12] was the first act that officially established the CRP as it is known today. CRP is overseen by the United States Department of Agriculture (USDA) and has numerous programs, including state-, species-, and environment-specific, in operation today.

The Iowa Pheasant Recovery is a CRP State Acres for Wildlife Enhancement (SAFE) program that has been specifically designed to increase populations of ring-necked pheasants in areas where their preferred habitats have been eliminated. All enrolled land must provide a habitat block of nesting cover, winter cover, and a winter grain food plot [38]. Restoring top quality winter and nesting / brood-rearing habitat can help pheasant populations recover and could boost annual harvest by 100,000 roosters [26].

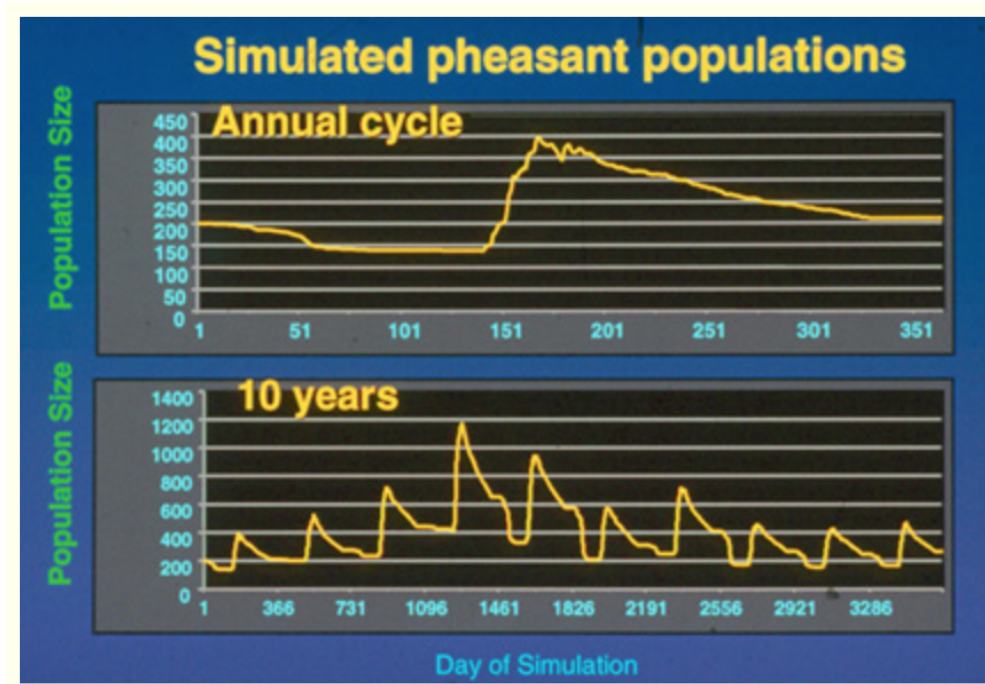


Figure 2: **PHEASCAPE Model** - Population dynamics over a ten year period, from [9]

2.3 Spatially-explicit Agent-based Models

Agent-based models (ABM), also called individual-based models (IBM), are used for simulating the actions and interactions of autonomous individuals. Most ABMs are composed of four elements: (1) agents specified at a particular scale, (2) decision-making heuristics, (3) learning rules or adaptive processes, and (4) a clearly-defined spatial environment. ABMs are useful for problems that examine behaviors because they can examine and simulate agent behavior at different hierarchical levels. ABMs can be used to investigate what happens to the environment and dynamics between entities because of actions by individuals, as well as what happens to individuals because of what the system does [43]. ABMs are also stochastic in nature, and so multiple replicates of scenarios must be run in order to determine the average behavior.

NetLogo is an agent-based programming language and integrated modeling environment. Originally designed and built in 1999 by Uri Wilensky [52], NetLogo is open source and freely available from the NetLogo website [54]. Over the years NetLogo has grown in popularity for agent-based modeling due to the ease in which users can learn the software and begin writing codes. Many researchers have built ABMs using NetLogo to explore various scientific questions, including some related to population and territory dynamics of tiger populations [8], breeding synchrony in colonial birds [33], pesticide exposure and spatial dynamics in agricultural landscapes [30], and finding different forms of flocking [50].

2.4 Spatiotemporal Harvest Planning

Spatiotemporal harvest planning deals with the timing and spatial constraints associated with harvesting various entities - biomass and pheasants in this case - given different objectives. One concept that has garnered a lot of attention in the literature is the idea of a no-take reserve. Many studies have found that yield-maximizing solutions often include one or more no-take reserves that may change in size and location over time [29, 34, 39, 45]. The models in these studies used to model the system and its dynamics, range from individual-based models [45] and integer programming [44], to partial differential equation models [29, 39]. In their modeling study, Marshalek et al. [34] found that as the number of reserves increases, the number of species retained also increases. Additionally, adding reserves in landscapes with lower species diversity saves species at a higher rate than in landscapes with higher diversity. By definition, optimized spatiotemporal harvest plans are superior to non-optimized harvest plans [44]. An example of this can be seen in Ramage et al. [44] where they found “clear benefits of optimized spatiotemporal harvest plans relative to non-optimized harvest plans” when examining timber production in tropical forests. Integrating harvest planning with reserve design can lead to novel insights, though management practices are highly dependent on ecological characteristics of the landscape. Marshalek et al. [34] found several interesting interactions between harvest planning and reserve establishments, include that on landscapes with high species diversity and high conspecific aggregation, strategic harvest plans with no reserves saved more species than fixed-pattern, aggregated harvest plans with over 20% of stands set aside as reserves. Finally, it has been demonstrated that less aggregated harvest plans enhance biodiversity conservation [34, 45]. Marshalek et al. [34] recommends that future models should consider more combinations of optimal harvest planning and reserve design alongside economic and social considerations.

2.5 Perennial Biomass Feedstocks

Perennial bioenergy crops provide the feedstock for biomass energy production. Biomass energy production, or more broadly, bioenergy, is a renewable source of energy that is made from materials derived from biological sources. Sources of biomass include wood, wood waste, crop residue, straw, and bioenergy crops. Corn may be one of the more well-known bioenergy crops, however, perennial grass-crops like switchgrass and miscanthus are beginning to grow in popularity.

Using perennial grasses as a source of biomass not only contributes to the bioenergy market, but may also benefit wildlife. Often, perennial grasses simulate wildlife habitat which is beneficial, especially in agricultural landscapes where rowcrops have degraded and fragmented wildlife habitat [13, 24]. Harvesting of perennial grasses can also be delayed to accommodate nesting behavior and brood rearing. Typically, harvesting

operations occur during nesting season and can negatively affect wildlife, specifically avian, populations [37]. Postponing harvest does not come without consequences; there is a peak window in which to harvest biomass and delays past that period result in degradation of biomass [20]. This does not mean the biomass is not useful as a feedstock for bioenergy production. Rather, the energy content decreases and a larger amount of feedstock is required to achieve an equivalent amount of energy production that would have occurred if the bioenergy crops were harvested during the peak time. Quantifying this trade-off is one of the goals of this study.

3 Model Description

For this study, a spatially-explicit, agent-based model was constructed in NetLogo. Operating on a daily time step, the model was run over a 10 year period, with 100 replicates and the assumption of no land use change over time. The main purpose of this model is to simulate ring-necked pheasants in agricultural landscapes that include bioenergy crops. For a detailed description of the model, see the ODD Protocol in Appendix A.

3.1 Site Description

A selection of agricultural fields in Iowa, USA were chosen as the base landscape for this analysis (Figure 3). The total simulated area is 2.879 km² and contains CRP SAFE acres in the form of nesting cover, winter cover (switchgrass), and a food plot. Through collaboration with the ANTARES project, geospatial data of the chosen area were acquired and imported into the ABM. The study region represents a typical agricultural area in Iowa. The majority of land is used to grow corn and soybeans with some patches of deciduous forests interspersed on the landscape. There are wetlands (herbaceous and woody) present as well as some hay, alfalfa, oats, and grasslands. The CRP SAFE Pheasant program has strict requirements on the design of enrolled land and the types of species that can be planted. All blocks of land must be at least 20 acres (0.081 km²) and no larger than 160 acres (0.647 km²) with winter cover taking up 25% of the block, a food plot on 10% of the land area, and the rest of the land being used for nesting cover. The site chosen for this analysis includes all of these necessary requirements, in addition to some surrounding land. Establishing winter cover and a nearby food plot is key to ensuring that pheasants survive through the winter. The winter cover protects them from predation and cold temperatures, while the food plot ensures they can access enough high caloric food to survive the cold. While the need for nesting cover may be more self-explanatory, adequate nesting cover that is left undisturbed until hens have finished brooding greatly increases juveniles chance of survival.

3.2 Agents and Processes

There are four agents in this model: pheasants (male and female), tractors, hunters, and vegetation. Pheasants, tractors, and hunters all have submodels which they can execute in order to simulate real-life dynamics.

Pheasants: Male and female pheasants have variables for their age (in days), energy (in kg), the number of attempts used to forage for food (4 total), the identity of their mother, whether they are reproducing, and the size of their reproductive territory (in km) if they are reproducing. Males also have variables that describe their desirability to females when attempting to reproduce, the number of attempts to establish a

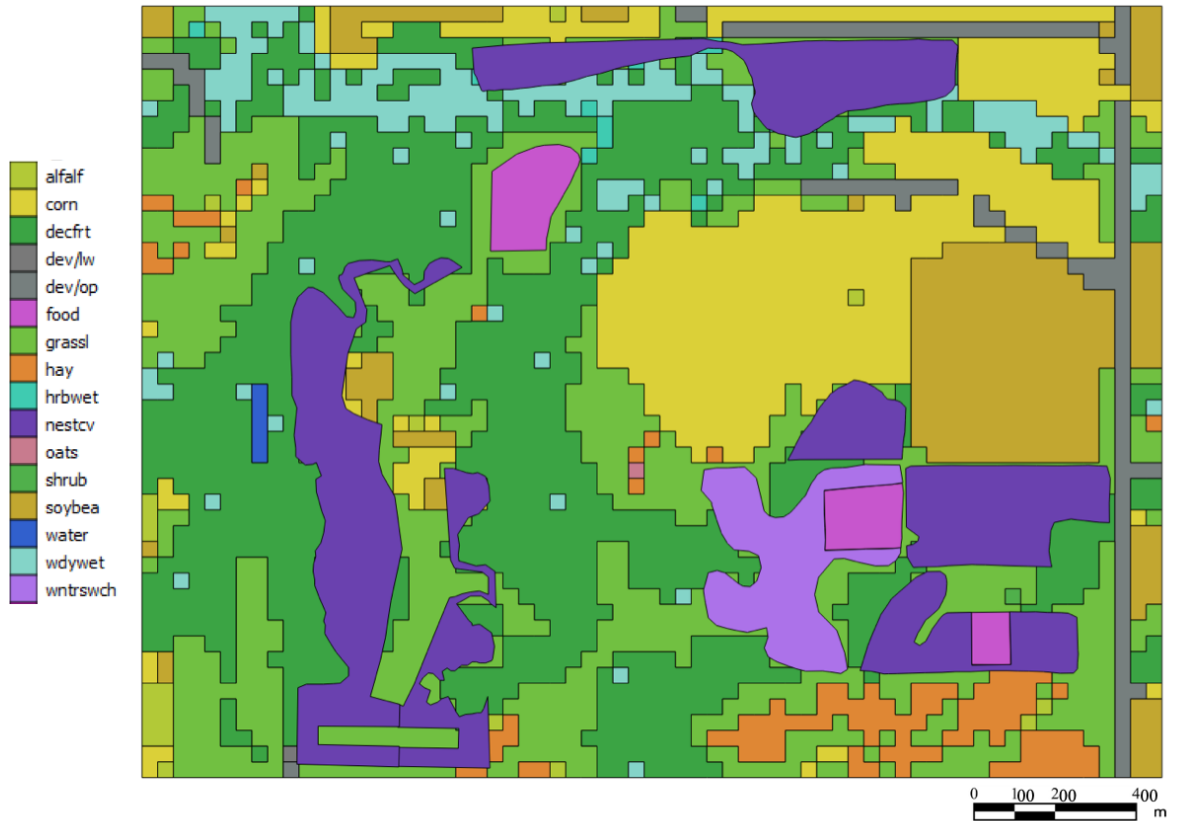


Figure 3: **Study region** - the possible landuses in the study region are alfalfa (alfalf), corn, deciduous forest (decftr), developed (dev/lw and dev/op), food plot which is CRP SAFE land (food), grassland (grassl), hay, herbaceous wetland (hrbwet), nesting cover which is CRP SAFE land (nestcv), oats, shrubland (shrub), soybean (soy), water, woody wetland (wdywet), and winter cover: switchgrass which is CRP SAFE land (wntrswch)

harem (2 total), and the size (in km) of their potential harem. Females have variables that indicate whether they have established a nest, the location of their nest, and the number of eggs they have laid (between 7 and 15 [17]). All juveniles (age ≤ 77 days) who are born during the simulation period begin with age 0 on their first day of life. The 200 pheasants that are created when the model is initialized are assigned an age between 77 and 730 days, because all initialized pheasants are adults. Similarly, pheasants are born with 0 energy, and are initialized with between 0.1 - 1.1 kg (females) and between 0.9 - 3.0 kg (males) [17]. Upon creation, males are assigned a desirability value between 0 and 1, which influences their harem-radius, or the area in which males may search for females in attempts to reproduce.

In the `Forage` process, both male and female pheasants forage, or search for food. All pheasants have 4 attempts to move to a patch with food energy (i.e., has a vegetation the pheasant can eat, like corn). The value of the food the pheasant eats is added to their current energy value. Pheasants move one patch in any heading when searching for food, unless they are a juvenile, then they stay within 4 patches of their mother. Only males have the process `Lek`, which they do at the beginning of the reproductive season. During this procedure, males have 2 trials to establish a harem. Males search the circular area with their harem-radius for available females to reproduce. Their harem-radius is determined by equation (1).

$$harem - radius = 2 * desirability + 5 \quad (1)$$

Any females that are inside a male's harem-radius then belong to that harem. If a female falls within the harem-radius of multiple males, then she will reproduce with the male who has the larger desirability value. Once lekking is done, female pheasants will begin the process `Nest` if they belong to a male's harem. Females find a part of the male's harem that is not currently occupied by another female and then they establish their nest at that spot. When a female establishes a nest, she will lay her eggs (between 7 and 15). Next, a female will do the process `Incubate` by staying on her nest and only foraging for food near their already established nest. After a nest has been incubated for the required amount of time, the process `Birth` will occur with a 50% chance that the hatchling is female. Outside of the reproductive season and foraging for food, the only other procedure that dictates pheasant movement is `Flock by Sex`. Pheasant execute this procedure in the fall and winter. Each pheasant looks for other pheasants of the same sex in a 5 patch radius from themselves. If they find another pheasant of the same sex, they move towards that pheasant to form a flock.

Finally, the last process that a pheasant may execute is the `Death` submodel. All pheasants die with a pre-determined probability (d) which is outlined in Table 2. However, the vegetation of the patch that a pheasant is occupying may provide cover (c) to the pheasant which could reduce their probability of dying

Table 2: **Death probabilities** - Probability of pheasant mortality given pheasant characteristics

Pheasant Characteristics	Probability (d)
Juvenile with mother	0.50
Juvenile without mother	0.78
Adult	0.21
Senior Adult	0.975

(d). Cover (c) is the vertical inches representing vegetation height. In this model, cover is either 0 or greater than 1. Based on equation (2), the total probability of death (P) for each pheasant is calculated.

$$P = \begin{cases} \frac{d}{c} & d \leq c, c \neq 0 \\ d & c = 0 \end{cases} \quad (2)$$

Tractors: Tractors have one variable, which describes the amount of biomass they have harvested (dry tons/km²). There is no limit placed on how much a tractor may harvest. Biomass Harvest is the only submodel that tractors execute. Depending on the scenario being run, tractors can either harvest using base-harvest or theory-harvest. Both work in nominally the same way. First, a tractor checks to see if the current patch is eligible for harvesting and whether or not it has been mown. If both criteria are met, the tractor will harvest the current patch and then repeat the process on the next patch. The next patch to be examined is different depending on whether base-harvest or theory-harvest is being used. In base-harvest, tractors emulate typical harvest practices by mowing the entire boundary of the field and then spiraling inward, to end the mowing path at the center of the field. Conversely, theory-harvest begins at the center of the field and spirals outward in its mowing pattern.

Hunters: Hunters have variables that describe their current target (only males), their accuracy in shooting their target, the number of attempts they have made to successfully hunt (total 6), the radius in which they may look for targets (2 cells), and the total number of roosters they have successfully killed. A hunter's accuracy is a random value between 0 and 1 that is assigned upon creation. The only submodel that hunters execute is Hunt, wherein hunters begin by searching for male pheasants (roosters) within their hunting radius. If there is a rooster within their search radius, that rooster becomes the hunters target. If there are more than one rooster within a search radius, only one rooster is randomly selected to become the target. If a random value between 0 and 1 is less than the hunters accuracy, then the rooster dies and the hunter's rooster count increases by 1. Otherwise, the rooster gets away, the hunter's hunt trials increase by 1, and the hunter will try to find a new target if they are eligible. As with harvesting by tractors, hunters have two different spatial options hunt-strip and hunt-radius. In hunt-strip, hunters begin at one part of the field and move forward, flushing pheasants out of the field. Hunter's search radius is limited to

only 180° in front of them. In `hunt-radius`, hunter’s movement and search radius are not restricted and they may move around the field regardless of heading.

Landscape: Finally, each vegetation patch describes what land use it is, the amount of food (in calories) that would be provided to a pheasant if they were to eat it, the amount of vertical cover (in inches) provided to pheasants, the biomass yield (tons/km²) that can be expected if the patch is harvested, and whether pheasants are allowed to nest in the patch. All food and cover values are were taken as averages from the literature [3, 14, 15, 46, 49] and are summarized in Table A.3. Only the CRP SAFE land (winter cover, nesting cover, and food plot) are available for harvesting, thus the biomass value of each patch of these types are a random value between 3.4 and 5.2 tons/km². This range of values is used because it is the average low and high estimates of the potential biomass yield from the mix of vegetation type used in CRP SAFE land [19]. According to the CRP SAFE program, oats, wheat, corn, grain sorghum, soybean, shrubs, conifers, native and introduced grasses, forbs, and legumes are all approved species for food plots, nesting cover, and winter cover [38].

3.3 Scheduling and Timing

All of the processes being modeled in this analysis are seasonally dependent as summarized in Figure 4. As a result, submodels are executed depending on current week and day. The model runs on a daily time step and the simulation period is 10 years. Multiple submodels can be run on the same day, however only one submodel executes at a time. Once all submodels have been executed in a day, time is incremented by 1 and the cycle begins again.

The timeline (Figure 5) shows every submodel that any agent may execute in the model. The length of the box represents the total time period for which a particular submodel is active. For some submodels like `lek` or `hunt-base` where agents have multiple attempts to accomplish some goal, the box represents the entire time period over which the agent may continue to try to accomplish the task. For other submodels, like `birth`, the box represents the period of time over which an event may occur, however the event is a singular occurrence and will not occur more than one time over the allowed period of time. The “one-cut” and “two-cut” boxes overlap because part of their execution happens at the same time during the year. These two submodels would not be executed at the same time in a model run. Only one tractor harvest submodel is executed per scenario.

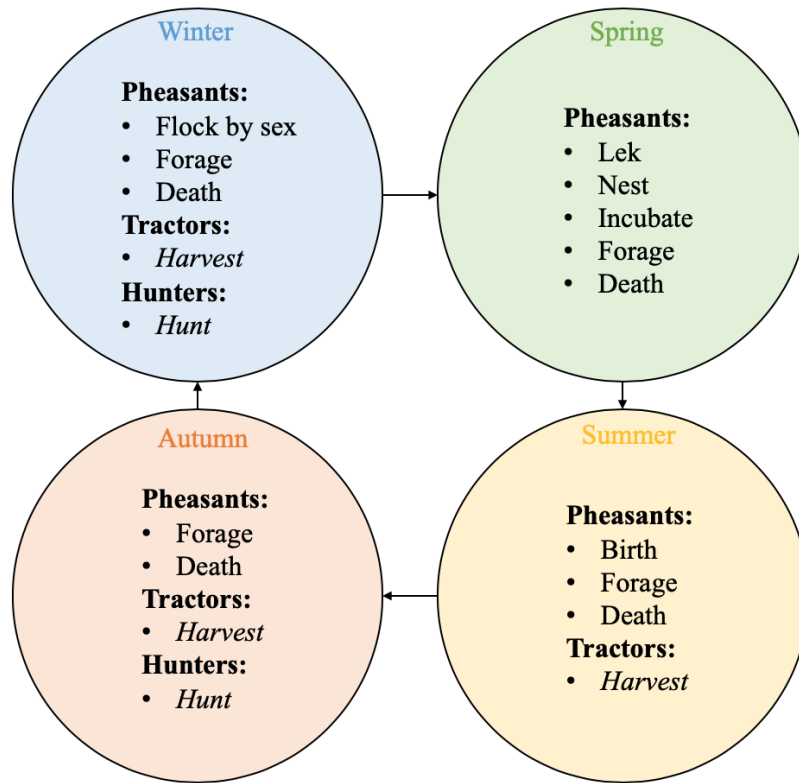


Figure 4: **Basic timing of model** - the model operates seasonally in that submodels executed by entities are time-dependent; submodels that are in italics can occur in listed seasons, but change timing depending on the scenario that is being run

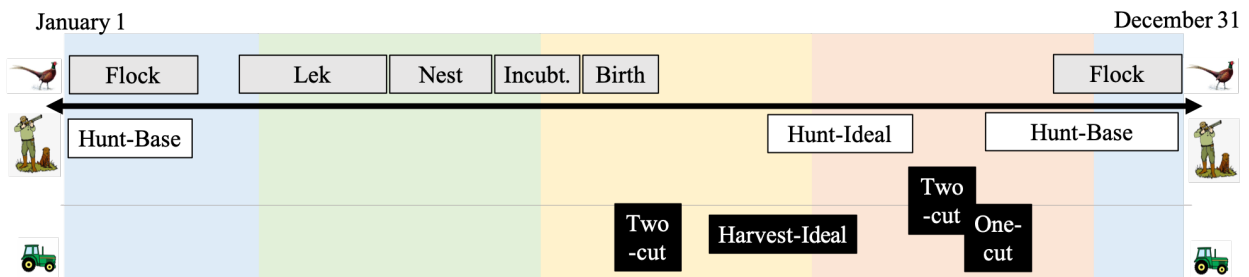


Figure 5: **Timeline** - A typical year simulated in the model with blue representing winter, green for spring, yellow for summer, and orange for autumn; grey boxes represent pheasant submodels, white boxes represent hunter submodels, and black boxes represent tractor submodels

3.4 Interactions

While each agent has its own submodels to execute, there are some interactions between agents that occur (Figure 6). Firstly, pheasants interact with vegetation. Pheasants eat food from the landscape and utilize the cover vegetation provides to decrease their probability of mortality. Additionally, pheasants are allowed to nest only on certain land types. Hunters only interact with male pheasants in that they hunt and kill them, with a certain accuracy probability. Tractors interact with both vegetation and pheasants. During harvest time, tractors will harvest CRP SAFE land only for biomass. If a tractor encounters a pheasant in its path, the pheasant dies.



Figure 6: **Interactions between agents** - this shows which agents are represented in the model and how each agent directly interacts with the other agents

4 Simulation Experiment

One of the goals of this analysis is to evaluate different spatiotemporal harvest strategies for both biomass and pheasants. To this end, a set of simulation experiments have been planned to compare different spatial and temporal plans for tractors and hunters (illustrated in Figure 7). For now, only scenarios 2 and 3 (S2 and S3) are executed and evaluated. The first step of future work will be to evaluate the remaining scenarios.

Tractor (spatial): The inward-spiral shown in Figure 7 represents the typical way fields with bioenergy crops are mowed, as opposed to back-and-forth row mowing for traditional crops. The tractor will begin at a point on the outskirts of the field and mow around the edges of the field, slowly making its way to the center of the field. This is the most common way to mow a non-corn field for a couple of reasons: (1) by following the natural curves of the field, the tractor does not have to slow down while making turns, (2) it is easy to pick a starting point for mowing, and (3) the mowing path is simple to follow without the need for technology or prior planning. However, this mowing path is not ideal for wildlife as it pushes them to the center of the field and traps them there. Conversely, the outward-spiral is, theoretically, considered the best mowing strategy for protecting wildlife [17, 18, 32]. By beginning in the center of the field and slowly mowing outward, wildlife can be flushed from the field. Although it may be the best path for wildlife, it may not be the most efficient or practical. First, prior to mowing, the farmer must determine where the center of the field is and then physically move the tractor to that spot. Second, without being able to see the boundary of the field, the path the tractor is to follow is less certain, resulting in the need for additional planning beforehand, slower mow-times, or, GPS-enabled tractors, all of which translate to lost productivity.

Tractor (temporal): This is the only category in the experiments that has three possible plans. This is because there are two possible strategies that are traditionally used when harvesting biomass, a one-cut system and a two-cut system. Even though there is no significant difference in harvested biomass [1] between the two systems, both one-cut and two-cut systems are used in Iowa. In the one-cut system, per the name, mowing occurs once and this is generally after the first kill frost, or November 1st. In the two-cut system, the first cut occurs in late June to early July, while the second cut happens in mid-October. Even though either system could be used as the baseline, we decided to investigate both cutting systems because the timing of the cut coincides with important dates in pheasants life cycle and may have a greater effect on pheasant population dynamics. The ideal time to harvest biomass in order to benefit pheasants is once between August 1st and 15th [3, 37]. This is because by this time, pheasants have finished reproducing and hens are no longer using the crops as brooding cover. In fact, they have recently stopped brooding and are transitioning to their winter activities in which they flock by sex and utilize winter cover.

Hunter (spatial): Typically when pheasant hunting, hunters will begin at one edge of the field and

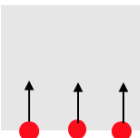
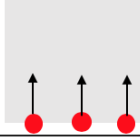
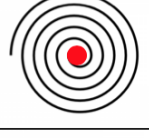
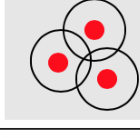
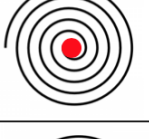
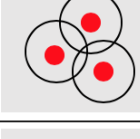
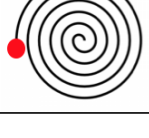
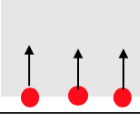
Scenario	Tractor (spatial)	Tractor (temporal)	Hunter (spatial)	Hunter (temporal)
1		One-Cut: mow once after Nov 1		Oct 31 – Jan 31 (93 days)
2		Two-Cut: first cut late June-early July, second cut Oct 15-17		Oct 31 – Jan 31 (93 days)
3		Mowed once between Aug 1-15		Aug 20 – Sept 30 (42 days)
4		Two-Cut: first cut late June-early July, second cut Oct 15-17		Oct 31 – Jan 31 (93 days)
5		Mowed once between Aug 1-15		Aug 20 – Sept 30 (42 days)

Figure 7: **Simulation experiments** - red points indicate starting point

move systematically across the field in one direction to flush the pheasants out into the open, as represented by the 1st, 2nd, and 5th graphic in Figure 7. The other spatial strategy investigated is a radial approach. In this approach, hunters search for pheasants within a set buffer around themselves. Rather than flushing pheasants from the field, hunters will seek out pheasants in this strategy and approach them.

Hunter (temporal): The official pheasant-hunting season in Iowa runs from October 31st to January 31st [48]. This hunting period is 93 days long and occurs when pheasants are utilizing winter cover. The other potential hunting period that is tested is approximately half of the official hunting season (42 days) but occurs earlier in the year, namely from August 20th to September 30th. During this time period, pheasants are transitioning from brood cover to winter cover and thus may be easier to spot or flush from hiding.

Five scenarios were constructed using the above theories. There were created in order to fully test the spectrum of possible harvest strategies. While they are graphically summarized in Figure 7, they are also discussed briefly below.

- *Scenario 1* – This scenario utilizes tractor paths, hunting paths, and a hunting season that is typical of current practices in Iowa. As was discussed above, there are two different cutting systems that could be used in a baseline scenario. Hence, S1 will use the one-cut system.
- *Scenario 2* – S2 is the same as S1, except instead of using the one-cut system, it will examine the two-cut system.
- *Scenario 3* – This scenario incorporates all of the theoretical best practices as mentioned in the literature [1, 3, 35, 37].
- *Scenario 4* – This scenario is the first of two mixed scenarios. In this scenario, the spatial elements are from S3, and the temporal elements fall under S1 and S2.
- *Scenario 5* – This is the second mixed scenario. Here, the spatial elements are from S1 and S2, and the temporal elements reflect S3.

5 Results

5.1 Model Evaluation

Baseline Analysis

By running a baseline simulation, we are able to examine the pheasant population dynamics and ensure that population trends are consistent with observed data [10] and follow pheasant life history patterns, as described in Section 2.1. For the baseline analysis, 100 replicates of a 50 year simulation with no hunters, no tractors, and initial conditions of 100 male and 100 females (200 total) were conducted. The average population size, along with one interval of standard deviation is shown in Figure 8. The population begins at 200 pheasants and then increases to approximately 275, remaining around this value for the rest of the simulation which is consistent with pheasant populations in an area of approximately 3 km² [53].

Proportion of Births by Gender Analysis

In the baseline runs, the probability that a hatchling is born female is 50%. By varying this probability, we can examine the resulting population dynamics and ensure that the population size follows expected trends based on what is known about pheasant reproduction. The model was run 100 times over the 10 year simulation period with no hunters or tractors, and the probability that a hatchling is born male was varied at 20%, 40%, 60%, and 80% (Figure 9).

All subplots in Figure 9 exhibit cyclical change associated with spikes around birth season (on average each female births 7-15 juveniles) and subsequent declines since juvenile mortality is very high (50-78% depending on whether the mother is alive). Additionally, the pheasant population dies out when probability that a hatchling is born male is 80% (Figure 9, subplot 0.8) because there are not enough females to keep the population going. Conversely, when the probability that a hatchling is born female is high (80% and 60%) then the population explodes. These trends follow expected patterns in pheasant population dynamics. One male pheasant has, on average, twelve females in a harem. Thus, it is not important for many males to be alive in order to keep the pheasant population going. In fact, when the probability that a hatchling is born male is 20% or even 40%, the female population gets as high as 150,000 and 12,500 respectively. The question of resource use may also contribute to the disparity in population outcomes (reaching almost 150,000 females versus population die out) in that having fewer males may open up more resources for the females who are key in keeping the population going.

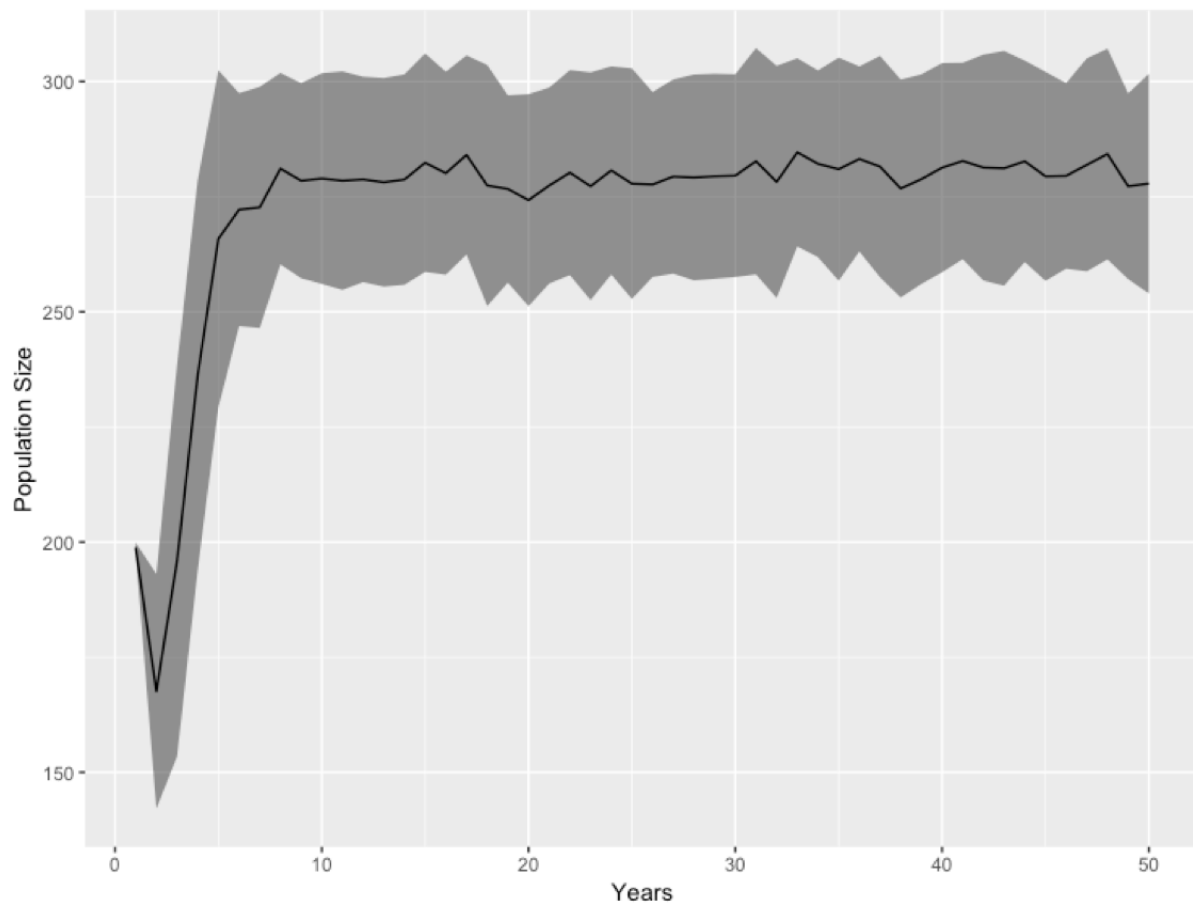


Figure 8: **Baseline Population Size** - This graph plots the average population size over 50 years. The black line represents the mean population size of 100 simulated populations. The surrounding grey region represents ± 1 standard deviation of the mean population size over 100 simulations.

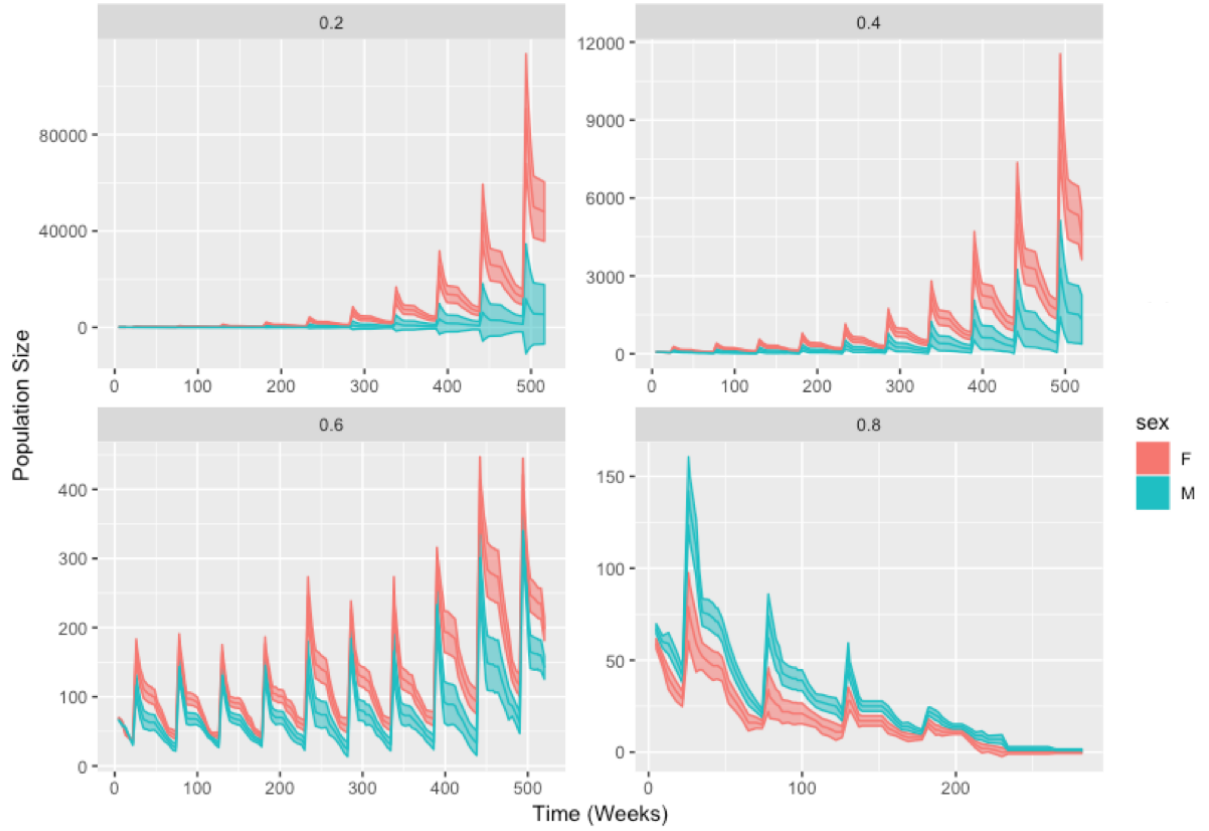


Figure 9: **Population dynamics under varied gender proportions** - Beginning in the top left, 0.2 subplot shows male (blue) and female (red) populations under 20%M/80%F proportion of hatchlings probabilities, 0.4 subplot shows populations under 40%M/60%F proportion of hatchlings probabilities, 0.6 subplot shows populations under 60%M/40%F proportion of hatchlings probabilities, and 0.8 subplot shows under 80%M/20%F proportion of hatchlings probabilities. Population size scale varies over graphs.

Spatial Distribution

During the 50 year baseline simulation, a snapshot of the model region was taken (Figure 10a). The small brown and red spots are the pheasants on the landscape. The number of pheasants occupying each land use was also recorded over time. Pheasant counts occurred on June 30th which is right after pheasants finish giving birth. Figure 10c illustrates the breakdown of pheasant use of each land type. In every year reported, the majority of pheasants are in CRP SAFE nesting cover, corn, and grassland areas which is striking given that by percentage, forest land is the most abundant land use in the study region (Figure 10b). However, the increased use of CRP SAFE nesting cover, corn, and grassland areas is expected based on pheasant spatial life history, as discussed in Section 2.1. These are areas in which females build their nests, so the fact that these land types have high occupancy during reproductive season is logical. Nesting cover, corn, and grassland are popular nesting sites for pheasants and ideal land types for new mothers to bring their broods. In this instance, the numbers reported by the model agree with expectations based on a literature review of pheasant spatial life history [6, 51].

Occupancy Trends

Finally, for the last step of model evaluation, we compared simulated data with observed pheasant occupancy data [11, 28] as shown in Figure 11. This is broken down by land category because pheasants use land types for different activities and thus occupy land at different densities. Here we are referring to overall habitat amounts available when discussing areas. Smaller datasets, of both modeled and observed data, lead to no definitive match ups between individual data points. Rather, trends of occupancy that are influenced by available area and land use category can be seen. Simulated pheasant density in CRP, developed, grassland, and trees were on average less than observed densities. Trees had the largest discrepancy between modeled and observed data. It appears that pheasants will densely utilize tree habitat. This may be because trees tend to provide much greater cover to pheasants than other land types found in an agricultural region. Forests provide tree canopy cover and minimal undergrowth, which leads to protective enclosures. Higher rates of cover provided by forests and the protective enclosure phenomenon are not built into this model.

Hay and row crops were the two land categories that had higher modeled densities than observed densities. Hay had the larger difference and this may be due to how data was categorized. The observed densities for hay also included things like small grains which were represented in a different land category in the model. Overall, there is a level of agreement between observed [11, 28] and modeled data which leads further credence to the ABM.

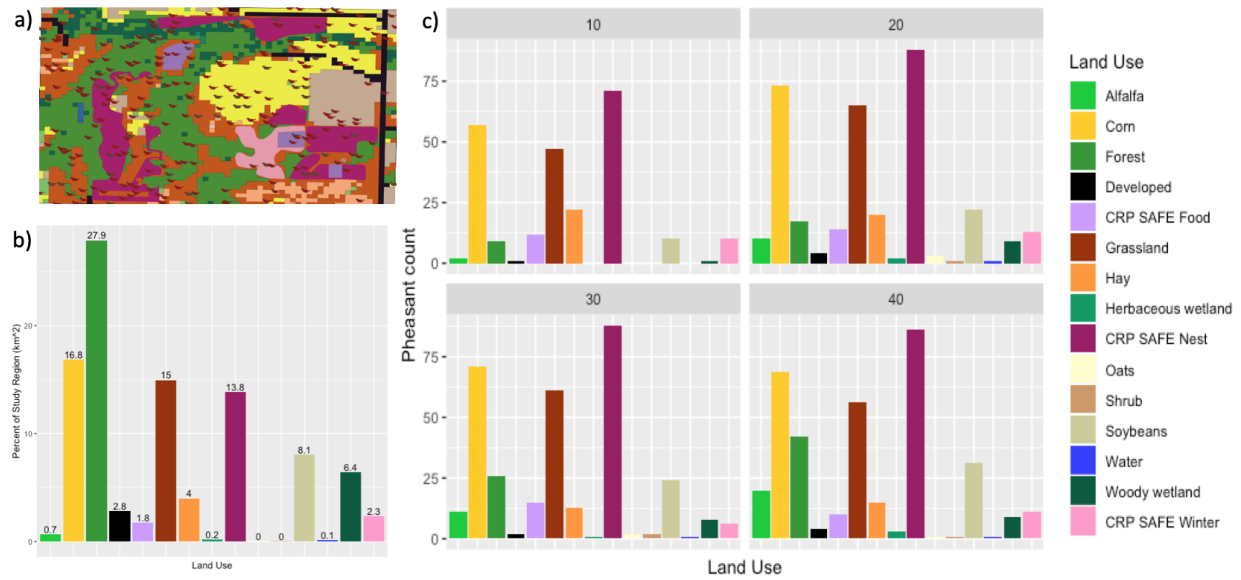


Figure 10: **Baseline spatial distribution and land use occupancy** - Overall, this figure illustrates the spatial distribution of pheasants in the study region and the land use that pheasants occupy during the baseline simulation. A snapshot of the model region during a simulation is shown in (a). The percentage of land use in the study region is shown in (b). Finally, (c) depicts the number of pheasants found in each of the land uses represented in the study region for years 10, 20, 30, and 40 during the baseline simulation.

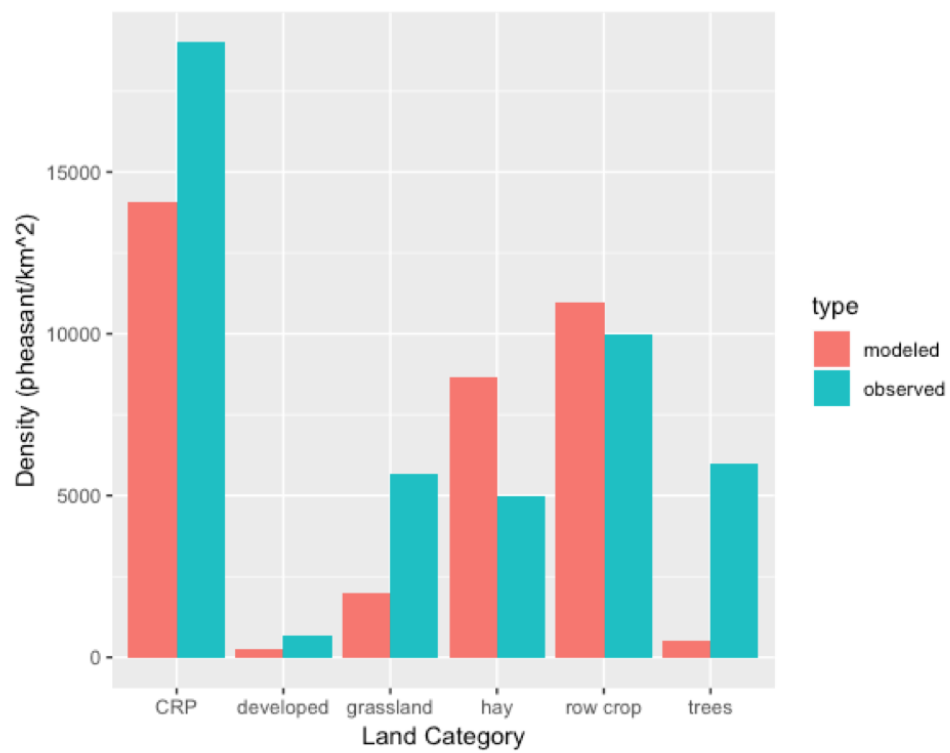


Figure 11: **Occupancy Trends** - Density (number of pheasants per km²) for each land category. Red is modeled data, blue is observed data [11, 28]

5.2 Scenario Evaluations

As discussed previously, only S2 and S3 (Figure 7) were run in this analysis. Each scenario was run over 10 years and replicated 100 times. These scenarios were chosen because they are representative of each of the variations on the spatial and temporal rules for tractors and hunters (i.e. inward spiral vs. outward spiral for tractor spatial, traditional two-cut vs. delayed harvest for tractor temporal, hunt strip vs. hunt radius for hunter spatial, and current hunting season in Iowa vs. a reduced hunting season for hunter temporal). In this way, we can begin to draw conclusions about various spatiotemporal rules and their effects on pheasant population, harvested biomass, and killed roosters.

Both S2 and S3 produced cyclic fluctuating populations (Figure 12) over the 10 year simulation period. Both populations began the simulation period with 200 pheasants total, and both ended with about the same (240 for S2 and 250 for S3). This indicates a steady population with minimal, but positive, overall population growth. In Clark [9], the simulated pheasant population begins a 10 year simulation with 200 total pheasants and ends with approximately 250 pheasants (Figure 2). Additionally, the maximum population at any time during the simulation was approximately 900 for S2 and 1000 for S3. Clark [9] also got a similar maximum population of 1200. Given the agreements between S2, S3, and PHEASCAPE results [9], we can further attest to the reliability of the model. This also lends credence to the following scenario results.

As with the baseline analysis, pheasant count by land use was taken at various times during the simulations (Figure 13). Each scenario was run 100 times, however these values in Figure 13 are from the first run only and not an average. The snapshot was taken halfway through the 10 year simulation during winter (January 15), spring (April 15), and summer (July 15). Land use occupancy does not change much between scenarios, but it does over seasons. This directly relates to pheasant's spatial life history and the habitat type that are needed for specific life processes. For example, in winter, pheasants tend to spend their time in switchgrass (CRP SAFE winter cover) and grassland because the height of the vegetation provides cover from predation and the cold. In spring, pheasants need to be in areas where they can successfully nest, such as nesting cover (CRP SAFE), corn, and grassland. Then in summer, males disperse and females rear their broods by taking them to areas with high nutritional value (such as corn and soy fields) but continue to stay near nesting sites (like grassland and CRP land) that can provide cover for their broods. These trends are illustrated in Figure 13.

The cumulative harvested biomass was tracked over time for each scenario (Figure 14). A two-cut system, or early cut, was used in S2 and the increase in harvested biomass can be seen on each step after the initial increase. Conversely, S3 only harvested once and so each step is smooth. The total biomass yield is approximately 10,000 tons/km² larger in S3 than S2. This is intriguing because both harvesting periods

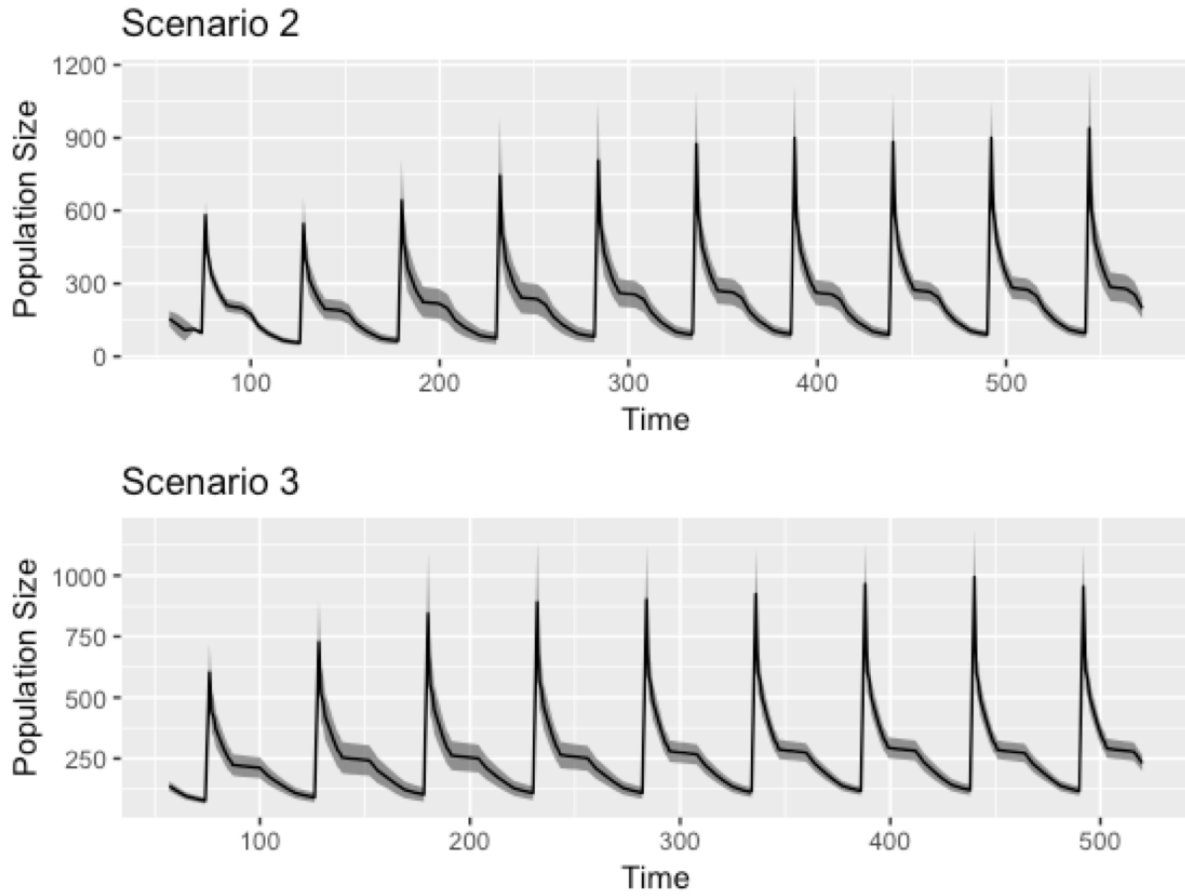


Figure 12: **Scenario Population Sizes** - Mean population size over 100 replicates for the 10 year simulation period of S2 (top) and S3 (bottom), buffer represents ± 1 standard deviation, population size scale varies between graphs

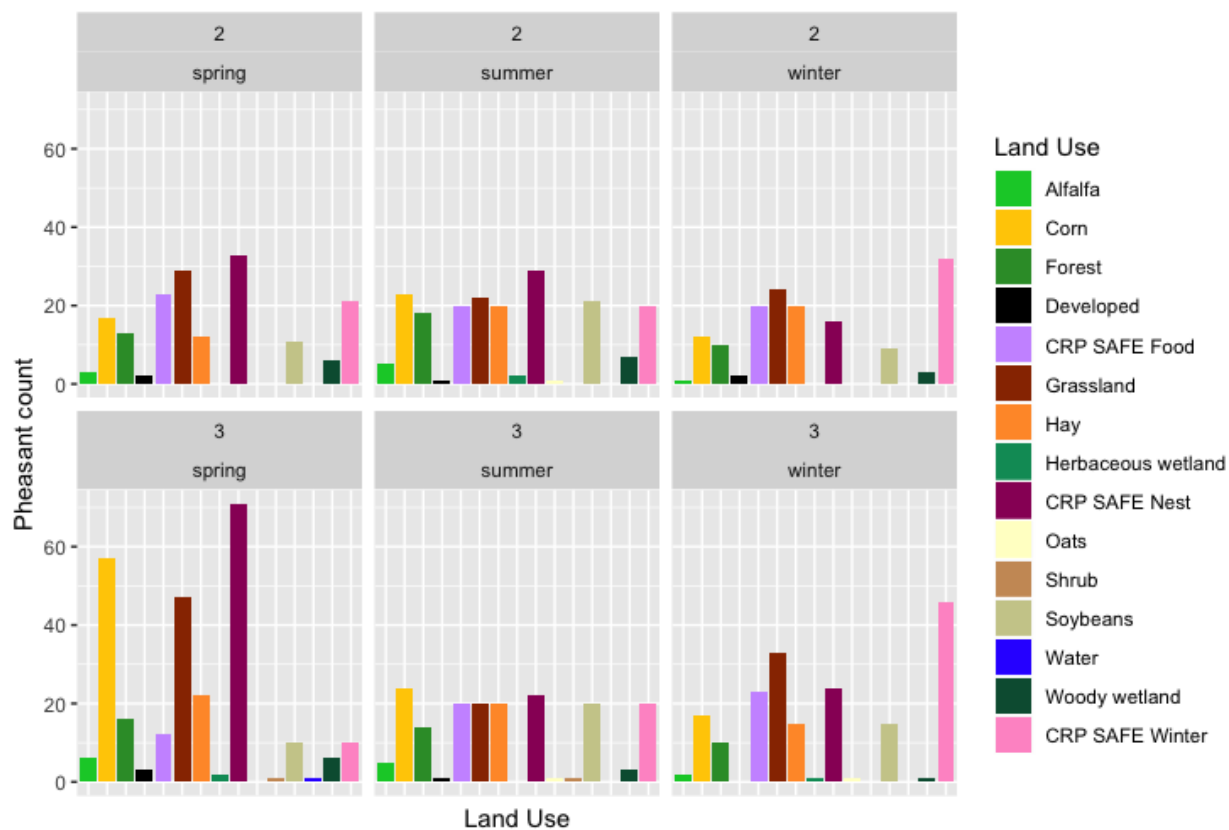


Figure 13: **Scenarios land use occupancy by season** - The number of pheasants occupying each land use represented in the study region during spring, summer, and winter. This is a snapshot from one replicate, not an average. S2 in top row and S3 in bottom row.

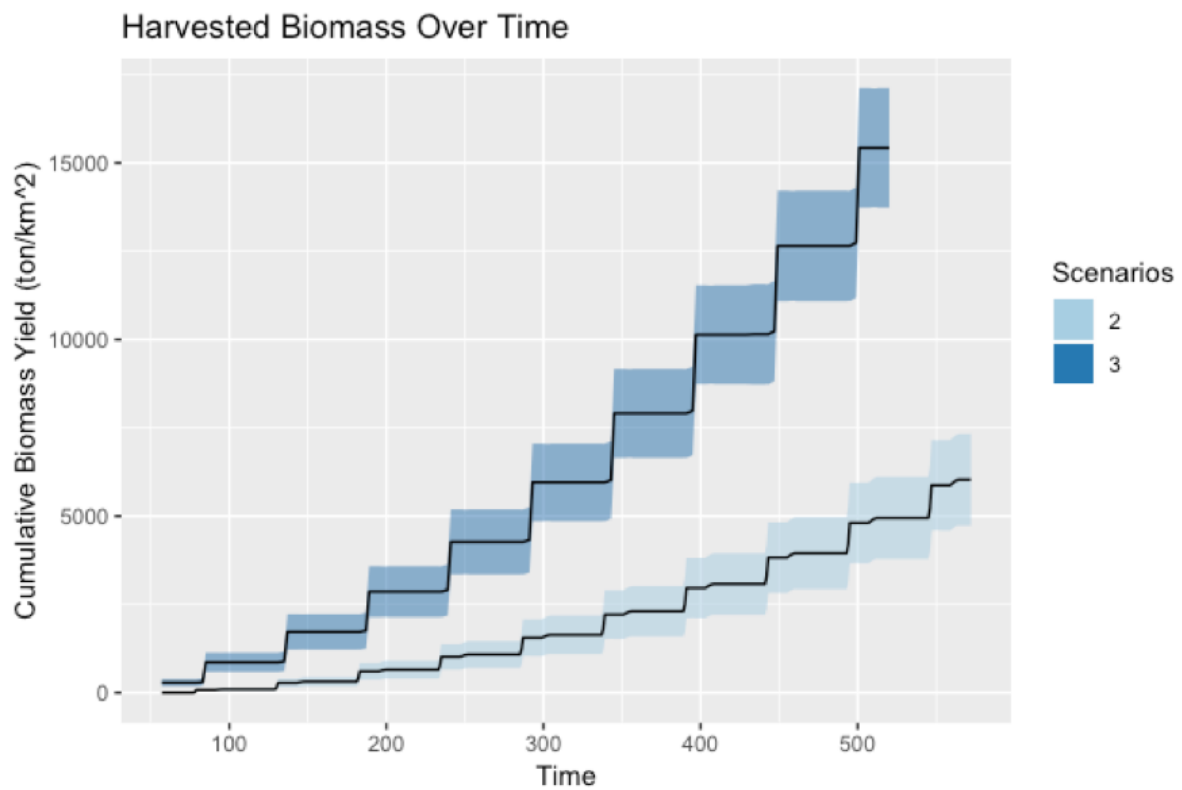


Figure 14: **Harvested biomass over time** - This figure shows the cumulative biomass yield (ton/km²) over time for both S2 and S3 scenarios. The dark line represents the mean biomass yield and the shaded regions represent ± 1 standard deviation.

last for 14 days total in both scenarios. Additionally, vegetation growth and decay is not currently dynamic in the model. Once a year, all vegetation parameters are re-initialized. What can be seen as spontaneous regrowth occurs after the second cut that happens in S2. Therefore, there is less overall biomass available on the landscape when harvesting is occurring in S2 compared with S3. This may account for such a large difference between the total biomass yield across S2 and S3.

The cumulative number of roosters killed by hunters was tracked over time for each scenario (Figure 15). A little more than double the number of roosters were killed by hunters in S2 compared with S3. However, the length of the hunting season in S2 is roughly double the length of the hunting season in S3 (93 days vs. 24 days). Proportionally, roosters were killed at the same rate which leads us to believe that the spatial strategy of hunters, strip versus radius, appears to have less of an impact on the number of roosters killed compared to the length of the hunting season. Figure 15 also has two black lines indicating the total number of accidental rooster deaths by tractors (S2 - 220 deaths, S3 - 52 deaths). The number of roosters accidentally killed by tractors may be so much lower in S3 because tractors are mowing once between August 1-15 which is after hens have finished using the habitat to rear their broods. In comparison, tractors were mowing in late June - early July and between October 15-17 in S2. The first cut occurs in the middle of pheasant's reproductive season when hens are nesting and rearing their brood. Hens are also not likely to abandon their brood in the face of imminent danger [17], so mother and brood deaths can be expected if tractors are disturbing their nesting site.

Finally, we want to evaluate the cyclic behavior of pheasant populations under various harvesting strategies. By plotting cumulative biomass harvested against population size (Figure 16) we are able to see the response of the pheasant population to harvested biomass. In S2, we see a fairly consistent harvested biomass value of around 5000 tons/km². Variation in these data points occurs in the number of roosters harvested by hunters which spreads from around 250 roosters to 600 roosters. Conversely, we see the opposite trend in S3 where data points are grouped around 150 roosters but vary from approximately 25000 tons/km² to 15500 tons/km². It is unclear what this means in terms of scenario evaluations because both S2 and S3 varied in all four components (spatial tractor, temporal tractor, spatial hunter, and temporal hunter). More simulation runs and analysis are needed to draw more definitive conclusions.

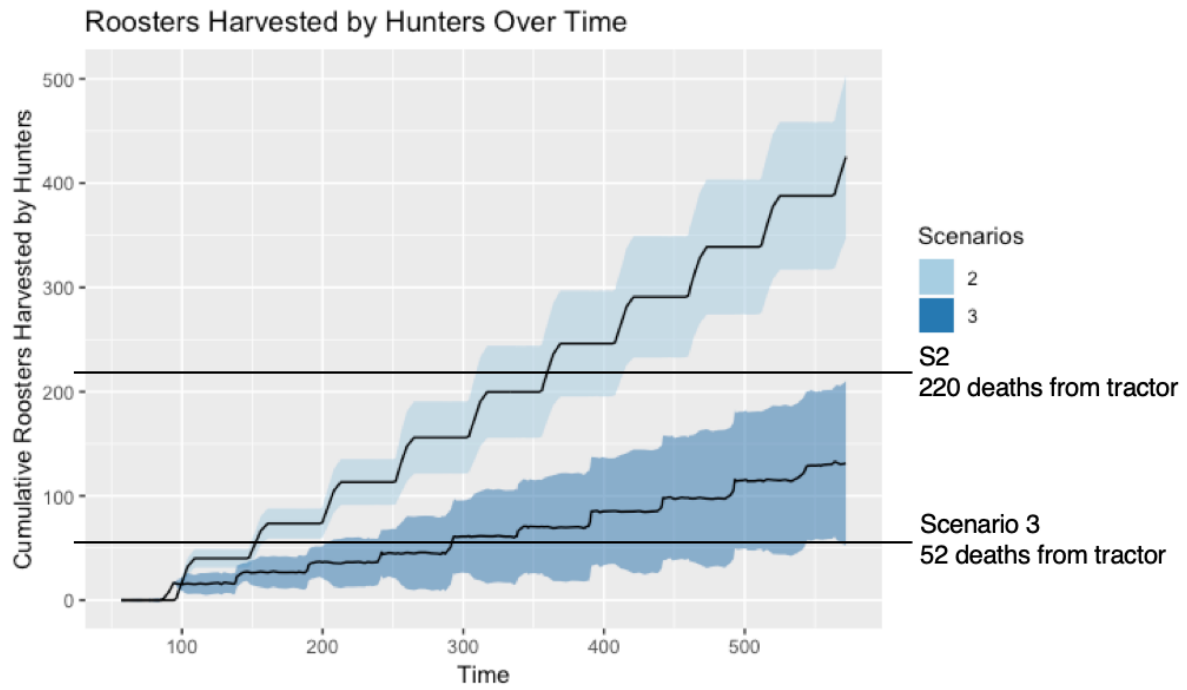


Figure 15: **Killed roosters over time** - This figure shows the cumulative roosters killed over time for both S2 and S3 scenarios. The dark line represents the mean number of roosters killed and the shaded regions represent ± 1 standard deviation. The total number of accidental rooster deaths by tractor is also shown for S2 (220 deaths) and S3 (52 deaths).

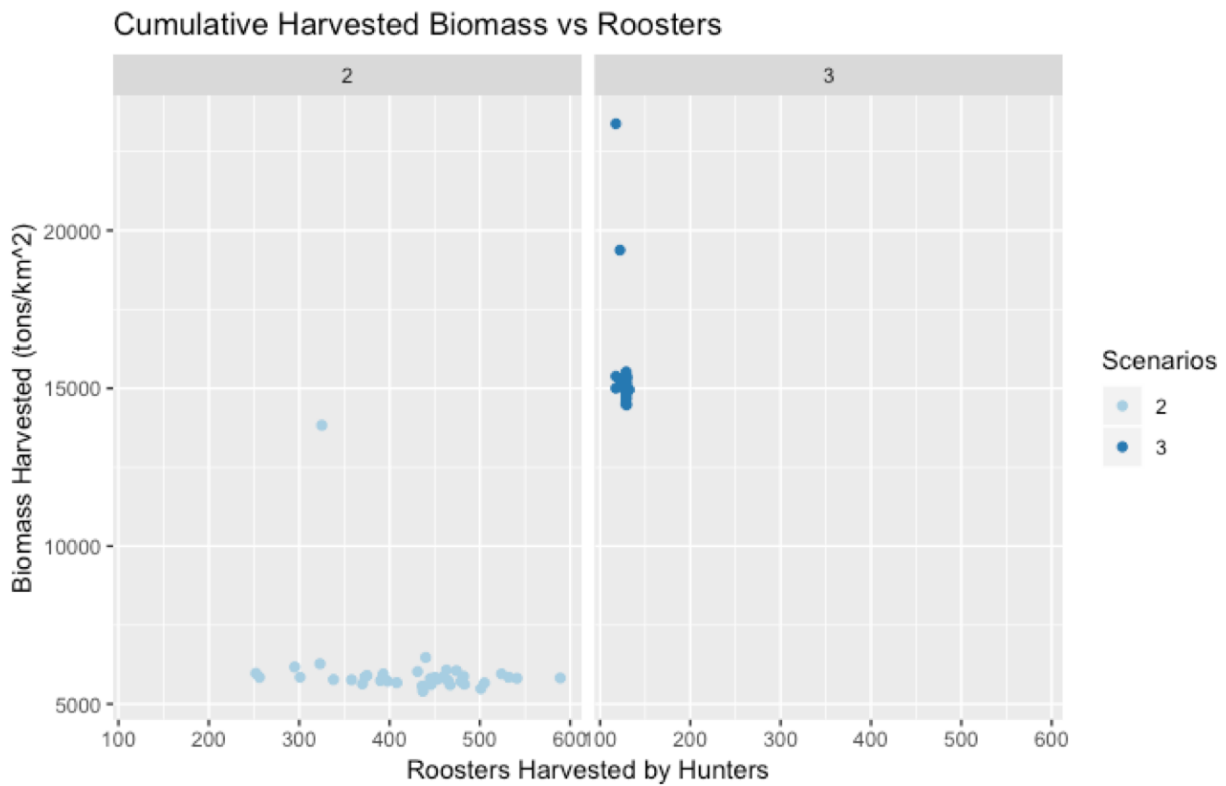


Figure 16: **Cumulative biomass harvested versus roosters harvested by hunters** - This figure shows the cumulative biomass harvested against pheasant population size for both S2 and S3 scenarios. Points represent the last data point from each replicate so there are no temporal trends present in the data. Additionally, because each point represents a replicate we can clearly see outliers in the dataset.

6 Conclusions

This study had three objectives: (1) create a spatially-explicit ABM that appropriately represents pheasant dynamics in an agricultural setting, and realistically represents the interactions between pheasants, the landscape, hunters, and tractors in the model, (2) compare modeled results with observed data and evaluate model performance in comparison to other pheasant models, and (3) run two harvesting scenarios in the model and evaluate their performance in terms of harvested biomass yield, killed roosters, and regular cyclic fluctuations of the pheasant population under these various management strategies. After extensive research into pheasant’s life history (Section 2.1), an ABM was constructed to represent pheasants in an agricultural setting. Both spatial and temporal aspects of pheasant life history was taken into consideration when creating the model. The success of the model is evident in that population trends match another model [9], and that loose trends can be drawn between simulated and observed [11, 28] occupancy by land use (see Section 5.1).

Two spatiotemporal harvest strategies of both tractors and hunters were evaluated. These scenarios were chosen of the five constructed, because they are representative of each of the variations on the spatial and temporal rules for tractors and hunters. Both scenarios were evaluated in terms of total harvested biomass yield, roosters killed by hunters, accidental rooster death from tractors, and the long-term sustainability of pheasant populations under the management strategies. In S3, roughly 10,000 tons/km² more biomass was harvested than in S2. Some of this may be due to the difference in spatial and temporal rules for tractors. However, it is likely that the majority of this discrepancy can be attributed to the fact that biomass values did not change over time. Once a year, regrowth would occur where all vegetation parameters were re-initialized. Re-growth did not happen between the two-cuts in S2 whereas, tractors in S3 harvested later and thus were able to harvest on land that had full biomass values.

More roosters were killed in S2 than S3, however, the hunting season was 93 days long in S2 compared to 24 days in S3. Proportionally, the hunters in S3 killed roosters at about the same rate as S2. This leads us to believe that spatial constraints on hunters are less important than temporal constraints. This may not be the case. A superficial reading of the results from this study allow us to draw limited conclusions suggesting that certain spatial and temporal rules for tractors and hunters are better than others, depending on one’s final objective. The biggest caveat attached to these results, is that of the two scenarios simulated and evaluated, there were no overlapping spatial and temporal rules between either tractors or hunters. This makes it difficult for us to parse out the cause behind our results and doesn’t allow us to draw large over-arching conclusions. We can, however, draw smaller conclusions like tractor harvesting during the reproductive season will lead to higher accidental rooster deaths by tractors, and that the longer hunters are allowed to hunt pheasants on the landscape, the larger the overall number of roosters harvested by hunters will be. In

the end, the largest take-away is that more work is needed. Below is a list of planned future work:

- Run the rest of the spatiotemporal harvest scenarios, complete a similar analysis, and see how all five scenarios compare. Or, run a complete enumeration of all scenarios based on spatial and temporal rules of tractors and hunters.
- Create submodels that the landscape may execute in order to have dynamic growth and decay of vegetation.
- Only nesting cover, food plots, and winter cover are harvested. While this makes sense because we are investigating harvest strategies for biomass, we would like to add in harvest practices of corn and soybeans. Both of these crops dominate the Iowa agricultural landscape and we think it would be important to consider their harvesting on pheasant populations.
- Climatic factors, especially rainfall, can have large effects on pheasant populations. Incorporating climatic factors into the model could have an interesting effect on pheasant populations, vegetation growth, biomass yields, and even hunting practices (e.g. more extreme winters may prohibit hunting activities).
- We investigate two spatial hunting patterns in this analysis. In the future we would like to include no-take reserves in the hunters' spatial rules.
- The model is currently run with a starting population of 100 female and 100 male pheasants. We would like to run the 50 year baseline and 10 year scenarios with different starting population levels and distributions to see the effects of initial conditions on the resultant system dynamics.
- Per Iowa regulation, hunters are allowed to bag no more than 3 roosters per day. We would like to explore higher and lower bag limits.
- Refine pheasant and tractor interactions to incorporate avoidance behavior of tractors by pheasants.

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Appendix

A ODD Protocol

A.1 Purpose

The main purpose of this model is to simulate ring-necked pheasants in agricultural landscapes that include bioenergy crops. This is done in order to determine how bioenergy crops, which can be substituted for pheasant habitat, affect pheasant population dynamics and their spatial life history. Ultimately, this model will be used to help determine harvest strategies of both biomass and pheasants. Specifically, this study is examining agricultural fields in Iowa, USA (Figure A.1). The following description follows the Overview, Design concepts, and Details (ODD) protocol as laid out by Grimm et al. [22].

A.2 Entities, State Variables, and Scales

This model has four entities: pheasants (both male and female), tractors, and hunters, which are agents, and vegetation, which is represented as patches. The model is spatial: average fields in Iowa are simulated which serve as habitat for pheasants, and the landscape being simulated is 2.879 km². The model world is two-dimensional with each cell representing 0.06 km x 0.05 km on a 24 x 39 cell landscape. World wrapping is turned off so the space does have borders.

Both female and male pheasants have state variables for their age, their mass (in kg), the number of attempts at acquiring food, whether they have established a territory for mating, the area (in cells) of their territory (set to 0 if they have not established a territory), who their mother is, and the flock they belong to during winter, along with nearest pheasants of the same gender to help them form flocks. Each female pheasant additionally has state variables for which harem she belongs to, whether she has established a nest, the number of eggs she lays, and the location of her nest. Each male pheasant has state variables describing their desirability to females, the number of attempts to attract females (lekking behavior), whether they have established a harem, and the area (in cells) of their harem (set to 0 if they have not established a harem). Pheasant state variables are summarized in Table A.1.

Tractors have state variables that describe the amount of biomass they have harvested (dry ton/km²). This variable is called `yield` and can range from 0 to infinity. Hunters have state variables that describe the current target of their hunting efforts, their accuracy in hitting their target, the number of attempts they have to successfully hunt male-pheasants, the radius around themselves in which they can look for male-pheasants to hunt, and the total number of successfully killed roosters. Hunter's accuracy and the distance in which they may hunt are randomly assigned. Additionally, hunters may only kill up to three roosters per day. These state variables are summarized in Table A.2.



Figure A.1: **Project study region (Iowa, USA)** - this is the current land use (as of 2017) for Iowa, data from USDA

Table A.1: Pheasant state variable explanations and values

Pheasant Variable	Description	Value(s)
energy	Total mass (kg) of individual pheasant	$[0, \infty)$, female avg 0.1-1.1, male avg 0.9-3.0
age	Age (in days) of pheasant	$[0, 1095]$
food-trials	Number of attempts to find food	4
mom	Identifies the mother of each pheasant	female-pheasant ID
lek-trials	For males only, the number of attempts to establish a harem	2
desirability	For males only, a random value assigned at birth that describes how attractive they are to female-pheasants	$[0, 1]$
territorial?	Established territory for mating	True/False
terr-size	The area (in cells) of their mating territory	$0 \cup [5, 7]$
harem-radius	For males only, the area in which they may search for females and attempt to establish a harem, dependent on their desirability	$[5, 7]$
harem-num	For females only, identifies which male's harem they belong to	male-pheasant ID
est-nest?	For females only, established a nest	True/False
nest-site	For females only, the location of their nest site	patch ID
eggs	For females only, the number of eggs a female-pheasant has laid	$[7, 15]$

Table A.2: Hunter state variable explanations and values

Hunter Variable	Description	Value(s)
target	Identifies the current male-pheasant that an individual hunter is trying to kill	male-pheasant ID
accuracy	The probability that a hunter will hit their target	$[0, 1]$
hunt-trials	The number of attempts one hunter has in a day to successfully bag a male-pheasant	6
hunt-distance	The radius (in cells) around each hunter in which they may look for male-pheasants to treat as a target	$[0, 1]$
roosters	The total number of male-pheasants that a hunter has successfully bagged, cumulative over a hunting season	$[0, \infty)$

Grid cells (i.e. patches) describe the landscape composition. Patches have state variables that describe the amount of energy provided to pheasants if consumed (calories), the amount of cover provided to pheasants (vertical inches), the amount of potential biomass yield to be harvested (3.4 - 5.2 dry tons/km²), and a boolean variable that represents whether pheasants are allowed to nest in the specific type of vegetation. Vegetation state variables are summarized in Table A.3. Even though each patch has each of these state variables, there are 22 different possible land uses in the landscape, and there are not necessarily parameters for every land use. For example, while some patches may fall under the category of “Developed” (e.g. road), pheasants would not be able to consume these patches or receive any nutritional value from them. Thus, these variables take on the value of zero. For the sake of thoroughness, they are included in Table A.3.

The model runs on a daily time step and is seasonal, meaning that the processes that are executed are time-dependent. Model scheduling is discussed in more detail in the next section.

A.3 Process Overview and Scheduling

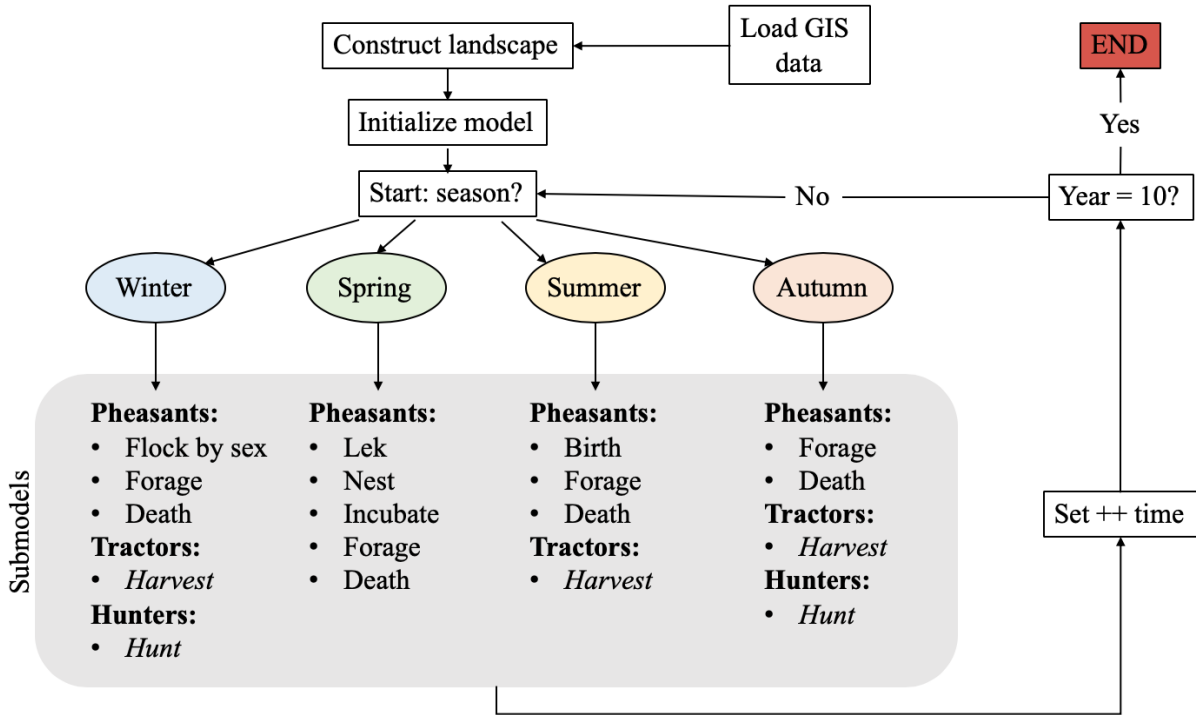
The following processes run on a daily time step in the order shown in Figure A.2. Activities related to reproduction and parenting are described in detail in the Submodels section.

Seasons determine which submodels are executed in the model, because pheasant life cycles and harvesting are time dependent. First, all input data is imported and the model landscape is constructed. The model is initialized and then all following processes occur randomly within their particular season. Each submodel within a season is run on a daily time step, once each submodel is completed, time will advance and the cycle will begin again. The model will continue to run for 10 years and then it will stop. Seasons are defined as follows:

- Winter: December 1 - February 28
- Spring: March 1 - May 31
- Summer: June 1 - August 31
- Autumn: September 1 - November 30

Table A.3: Vegetation state variable explanations and values

Land Use	Food (cal)	Cover (<i>c</i>) (inches)	Biomass (tons/km ²)	nest?
corn	5.9	[168, 192]	0	TRUE
soybeans	4.1	[36, 60]	0	FALSE
alfalfa	1.9	[24, 36]	0	TRUE
dry beans	0.8	[24, 36]	0	FALSE
hay	1.82	0	0	TRUE
oats	1.5	[48, 52]	0	FALSE
barren	0	0	0	FALSE
forest	0	[12, 62]	0	FALSE
developed	0	0	0	FALSE
grassland	3.3	[10, 30]	0	TRUE
wetland	0	[5, 10]	0	FALSE
water	0	0	0	FALSE
shrubland	1.3	[2, 24]	0	FALSE
sod/grass seed	3.3	[3, 4]	0	FALSE
food plot	12.6	[60, 80]	[3.4, 5.2]	TRUE
winter cover: switchgrass	4.4	[72, 82]	[3.4, 5.2]	TRUE
nesting cover	8.3	[54, 144]	[3.4, 5.2]	TRUE
winter cover: trees	1.1	[12, 42]	[3.4, 5.2]	TRUE
CRP (Other)	3.7	[50, 85]	0	TRUE

Figure A.2: **Diagram of ABM scheduling** - italicized submodels represent operations that may change depending on the scenario being run

A.4 Design Concepts

A.4.1 Basic Principles

The basic principle of this simulation is to replicate pheasant dynamics in combination with biomass harvesting and pheasant hunters in agricultural fields in Iowa. The pheasant populations reproduce and behave realistically based on data collected through behavioral and ecological field studies [5, 17, 21, 32, 51, 53]. Both biomass harvesting and hunter behavior are varied according to possible scenarios. These scenarios simulate baseline behavior and theoretically ideal behavior according to the literature [10, 18, 23, 31, 35, 36]. Geotagged tractor paths from various fields in Iowa [personal communication with Idaho National Laboratory] informed the biomass harvesting simulations. Hunter behavior is modeled after hunter testimonials and how-to guides [25, 48].

A.4.2 Emergence

When tractor and hunter predation is not included in the model and there is an initial population of 100 male pheasants and 100 female pheasants, we see the emergence of typical pheasant population dynamics, as discussed in Section 2.1.5. Pheasant populations will vary with hunting and harvesting schedules.

A.4.3 Adaptation

Male pheasants determine the size of their territory based on surrounding vegetation and the level of their desirability to potential mates. Female pheasants adopt the territory of their male mates after joining a male's harem. In the model, pheasants have limited attempts to find an unoccupied, habitable territory in which to establish a harem. For details, see the "Lek" submodel in 7.2.

A.4.4 Objectives

The objective of a pheasant is to mate and successfully reproduce. Their territory decisions are based on the vegetation around them. Mating decisions depend on availability of mates near and within their territory. Pheasants also seek out food. A tractor's objective is to harvest as much feedstock as possible in the allotted harvest season. A hunter's objective is to kill as many pheasants as possible given the daily limit of a haul.

A.4.5 Learning

The pheasants, tractors, and hunters have no learning capacity in this model.

A.4.6 Prediction

The pheasants, tractors, and hunters have no predictive capacity in this model.

A.4.7 Sensing

Pheasants can sense the gender and the mated-status of other pheasants within their search radius. This information drives movement and mating. They can also sense whether patches are occupied by other pheasants and the vegetation type there. Tractors can sense field boundaries (i.e., is patch eligible for mowing?) and whether an area has been mowed or not. Hunters can sense any male pheasants that are within their search radius.

A.4.8 Interaction

Pheasants utilize vegetation to provide cover, as a food source, and to satisfy habitat requirements of various life stages (such as reproduction). Hunters hunt pheasants during a specified hunting season. Tractors harvest various types of vegetation that result in agricultural yield. Tractors can also inadvertently kill pheasants during the harvest process.

A.4.9 Stochasticity

There are many processes in this model that occur stochastically. Whenever any entity (agent or patch) execute a procedure, the order in which the agents in the set execute that procedure is randomized. Additionally, there are decisions made by the agents or patches that are stochastic. Within this model, stochastic decisions by entities (agents and patches) are determined by drawing from a discrete number of available options with equal probability (i.e., from a uniform probability distribution) as described below.

Decisions using random number generation Let X be a decisions made with probability p . Each time decisions X is to be made, the uniform distribution $U[0, 1]$ is sampled to generate $y \in R$. The event X occurs if $y \leq p$, and does not occur otherwise. The following list details specific probabilities used in stochastic decision-making.

- When pheasant eggs are hatching, there is a 50% chance the hatchling is a female
- In the submodel death, there is a 0.005 probability of the death of a juvenile with a mother, and a 0.0078 probability of death of a juvenile whose mother has died or abandoned them to die. Adults die with probability 0.0021, and senior adult pheasants (older than 2 year) die with probability 0.975
- A hunter hits their target with a randomly assigned probability from the uniform distribution $U[0, 1]$

Decisions using random selection of entities Each entity is selected randomly with probability 50% of completing the following procedures on any given day.

- Male pheasants initiating courtship behavior (i.e. execute submodel lek)
- Female pheasants begin nesting
- Eggs in a nest hatch (submodel birth)

A.4.10 Collectives

Collectives in this model are the harems that male pheasants set up in order to breed. After juvenile pheasants are hatched, females previously belonging to the harems disperse by resetting all of their reproductive parameters and executing the forage submodel.

A.4.11 Observation

At each time step, we record the pheasant population size (both female and male counts), the current day, week, and year. When tractors and hunters are active on the landscape, we keep track of the total biomass yield that is harvested (dry tons/km²), and the cumulative pheasants killed by hunter (count), respectively.

A.5 Initialization

The model begins on January 1 of year 1. Initially, 200 pheasants (100 male and 100 female) are randomly placed in patches on the landscape. Each pheasant is assigned an age, energy, and desirability (males only) at random as described in section A.4.9 upon creation. Possible values that these parameters may take on can be found in Table A.1. The landscape is created from GIS data, however this data only defines the extent of the study area and what type of land use occurs where. As described in Table A.3, patch parameters can take on set values (i.e., Land Use and nest?) or randomly assigned from a range of values (i.e., Cover and Yield).

A.6 Input Data

The landscape of this model is created by importing GIS land data. The GIS Extension in NetLogo is used to import a shapefile of the landscape, which is then displayed and assigned appropriate patch values depending on landuse. We assign the starting coordinates of hunters and tractors. This ensures that these agents meet the restrictions on their movement, which depends on the land use.

A.7 Submodels

The submodels of the ABM are described here in detail. Note, when a set of agents executes a procedure, the order in which each agent of the set executes the procedure is random.

A.7.1 Forage

This procedure is executed by male and female pheasants. Initially, all agents set their food trials to zero. Until pheasants have either acquired food or used all of their 4 trials to find food, they will continue to search for food. If the patch a pheasant is inhabiting has food (denoted by patch variable `food-energy`), the pheasant will consume the available food on that patch by increasing their level of energy and the patch variable `food-energy` will decrease by the equivalent amount. Pheasants will then choose a random heading and move forward a random amount that is dependent on the amount of energy they have to move. If an agent is a juvenile pheasant ($\text{age} \leq 77$ days), then the individual must stay within a 4 patch radius of their mother. If a juvenile is further from their mother than the threshold, they will immediately face their mother and move towards her.

A.7.2 Lek

This procedure is executed by male pheasants only. Males have 2 trials to establish a harem. If they are unable to establish a harem within the allotted trials, then they will not mate during the reproductive season. Males possess a `desirability` parameter that is between 0 and 1, which is randomly assigned at birth. Following equation 3, each male also has a `harem-radius` which describes how large an area each male may search during a given time step in order to establish a harem. The radius of that circular area is given by

$$\text{harem} - \text{radius} = 2 * \text{desirability} + 5 \quad (3)$$

During a lekking trial, each male will check the patches that occur within their `harem-radius` for ownership by other males and whether the vegetation is suitable for nesting (boolean patch parameter `nest?`). If all requirements are met, then five things will happen. First, the male pheasant will set their parameter `territorial?` to true to indicate that they are in the process of moving through the reproductive cycle. Second, all patches within the harem radius will change their owner from nobody to the ID value of that particular male. The patches will also set `patch-harem-num` to the ID value of the male owner. Next, males will set their `terr-size` to the number of patches they own for their harem. Finally, all female pheasants that are currently within the male's breeding territory and not part of another male's harem will move towards that male, set their `territorial?` to true, set their `terr-size` as that of the male, and

set their `harem-num` to the `id` value of the male owner. If a female is within the breeding territory of more than one male, then she will mate with the male who has a larger desirability value. Only one male pheasant is allowed on a patch at a time. If a male is unable to establish a harem in the given trials, their `territorial?` parameter will remain `FALSE` and they will not participate in reproductive activities for the season.

A.7.3 Nest

This procedure is executed by female pheasants who belong to a harem (i.e. `territorial?` is `TRUE`) only. Females move randomly around in their harem territory and if they find a patch that is inside their harem territory and not occupied by another female, they will establish a nest in that patch (setting `est-nest?` to `TRUE` and establishing their `nest-site` as the current patch they are occupying). Once a female has established a nest, she will lay between 7 and 15 eggs at that site. The number of eggs that a female lays is randomly chosen. Females will continue to execute this procedure until either the nesting period is over or they establish a nest.

A.7.4 Incubate

This procedure is only executed by female pheasants who have established a nest and laid eggs (`est-nest?` is `TRUE`). Each day, females who have established nests will move ≤ 5 patches away from her nest in search of food and then move immediately back to their nest, regardless of whether their search for food was successful. This will continue throughout the entire incubation period.

A.7.5 Birth

This procedure is only executed by female pheasants who have established a nest and laid eggs (`est-nest?` is `TRUE`). When this submodel is initiated, each egg within a hen's nest will hatch in the same timestep (i.e. day), though female pheasants execute the `BIRTH` process randomly over the hatching period. There is a 50% that each hatchling will be female. Each new pheasant, depending on their sex, initialize the appropriate parameters.

A.7.6 Check Death

This procedure is executed by both male and female pheasants. All pheasants have a probability of mortality based on their age (summarized in Table A.4). However, vegetation may provide some cover to pheasants which could reduce their probability of dying. First, the vegetation of the patch is determined which provides

Table A.4: Probability of mortality given pheasant characteristics

Pheasant Characteristics	Probability (d)
Juvenile with mother	0.50
Juvenile without mother	0.78
Adult	0.21
Senior Adult	0.975

a value of the cover (c) provided. Next, the probability of mortality (d) is determined based on the pheasants characteristics. Based on equation (4), the total probability of death (P) is calculated.

$$\begin{cases} \frac{d}{c} & d \leq c \\ d & c = 0 \end{cases} \quad (4)$$

If the calculated probability is greater than a random float between 0 and 1, then the pheasant will execute the “Death” submodel. Otherwise, nothing happens and the pheasant continues to exist in the model.

A.7.7 Death

This procedure is executed by both male and female pheasants based on the submodel “Check Death”. Any patches within the territory of the dead pheasant will be reset to have no owner.

A.7.8 Flock by Sex

This procedure is executed by male and female pheasants. Each pheasant will look for other pheasants of the same sex in a radius of 5 patches from themselves. If there are other pheasants in the search radius, the individual will move towards them to form flocks of same-sex pheasants.

A.7.9 Biomass Harvest

This procedure is executed by tractors. First, the tractor will check to see if the current patch is eligible for harvest (`harvestable? = TRUE`) and whether or not it has been mown (`mown?`). If both of these criteria are met, the tractor will harvest the current patch. The tractor will then examine the boolean parameters of the next patch to determine if it should move to said patch, or a different patch. Choosing the next patch to investigate are different depending on which submodel (`base-harvest` or `theory-harvest`) is currently being executed. They are represented as two separate submodels in order to execute different rules of movement.

Base-Harvest In this submodel, tractors emulate the typical harvest practices by mowing the entire boundary of the field and then spiraling inward, to end the mowing path at the center of the field.

Theory-Harvest This submodel can be thought of as the opposite of base-harvest in that the tractor begins at the center of the field and then spirals outward to end at the boundary of the field.

A.7.10 Hunt

This procedure is executed by hunters. All hunters initially set their hunt trials to zero. Each hunter will continue to search for male pheasants to kill in each time step until they have killed 3 roosters or have used all of their hunt trials. If there is a rooster within a hunter's hunt-distance than that rooster becomes the hunters target. Each hunter possesses an `accuracy` parameter that is between 0 and 1, which is randomly assigned. If a random number between 0 and 1 is less than a hunters `accuracy` than the pheasant dies and the hunter's rooster count increases by one. Otherwise, the rooster gets away and the hunter increments their hunt trials by one and try again if they are eligible. This is the way that the hunter submodel operates. To introduce spatial variation, the hunt submodel is actually represented as two separate submodels (`hunt-strip` and `hunt-radius`) which are identical except for rules of movement.

Hunt-Strip In this submodel, hunters begin at one part of the field and move forward, flushing pheasants out of the field. Hunter's `hunt-distance` is limited to only 180 heading north in front of them and this is the only direction in which they move.

Hunt-Radius In this submodel, hunters movement and `hunt-distance` are not restricted by orientation. Wherever a hunter senses a potential target, they may move towards it regardless of heading.

Vita

Jasmine Kreig received her Bachelor's of Science degree in Environmental Science and Bachelor's of Arts degree in Mathematics in 2014 from the University of North Carolina at Chapel Hill. After graduating, she worked as a research assistant in Dr. Larry Band's Hydrology Lab at UNC Chapel Hill. In October 2014, Jasmine moved to Oak Ridge, TN to work as a post-bachelors for Dr. Henriette Jager in the Environmental Sciences Division at Oak Ridge National Laboratory. While there, she contributed to two chapters of the Department of Energy's 2016 Billion-Ton Report, Volume 2: Environmental Sustainability Effects of Select Scenarios from Volume 1.

Jasmine came to the University of Tennessee in August 2016 to pursue her Ph.D. in Energy Science and Engineering through the University of Tennessee, Knoxville and Oak Ridge National Laboratory's Bredesen Center for Interdisciplinary Research and Graduate Education. While working towards this goal, she earned her Master's of Science in Mathematics in August 2019. She will continue on in her graduate career to finish her Ph.D. with Dr. Henriette Jager, building upon this current work and integrating a landscape design optimization analysis.