Title: Agent-based modeling to evaluate the effects of harvesting biomass and hunting on ring-necked pheasant (*Phasianus colchicus*) populations

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Abstract

As the US strives to divest from fossil fuels, dedicated energy crops have increased in popularity because of their potential to serve as a renewable source of transportation fuel and biomass-generated electricity. Whereas the impacts of crop agriculture on biodiversity have been well-documented, less is known about the potential impacts that growing bioenergy crops could have on wildlife. In this study, we look specifically at the ring-necked pheasant (*Phasianus colchicus*) and how pheasant populations may be influenced by growing and harvesting bioenergy crops. We explored effects of temporal harvest strategies at the field scale on biomass yield and pheasant population size. To investigate, we developed an agent-based model (ABM) that simulates ring-necked pheasants, tractors, hunters, and vegetation classes. One such vegetation class is land that is enrolled in a Conservation Reserve Program (CRP) plan specifically targeting pheasant conservation. Using this ABM, we assessed four different landscapes—corn-dominated, CRP-dominated, grassland-dominated, and mixed landscape—under strategies that varied the time of harvest. We also used ecological valuation to compare scenario outcomes from an economic perspective. We determined that biomass yield and pheasant population size were sensitive to harvesting times. Our scenarios totaled between ~$931,000 (minimum) and $3.8 million (maximum) over all landscapes, though on average harvesting in late spring generated the most value ($2.45 million) and harvesting in fall was a close second in terms of profitability ($2.39 million).

1. Introduction

Perennial grasses provide more wildlife habitat compared to traditional row crops, resulting in increased bird diversity (Behrman et al. 2015). Additionally, perennial grasses can be harvested as biomass feedstocks (Florine et al. 2006). Thus, the opportunity with perennial grasses exists to contribute to wildlife conservation while simultaneously providing additional value to farmers. Biodiversity in agricultural landscapes has high value, however it can also provide economic value (Mishra et al. 2019). This value is revealed through hunters buying hunting licenses, paying farmers to hunt on their lands, and contributing to the tourist economy in many midwestern states (Mishra et al. 2019; US Department of Interior, 2016).

One game species that has contentious value in the conservation space depending on who you ask is the ring-necked pheasant (*Phasianus colchicus*). Non-hunters within the conservation community are less inclined to allocate limited conservation resources towards sustaining a non-native bird. Ring-necked pheasants are not invasive, but have been known to interact aggressively with other native birds and lay their eggs in other birds' nests (Dinsmore 2001). On the other hand, hunters highly value the ring-necked pheasant (*Phasianus colchicus*). Thanks in part to its popularity as a game bird, there are programs, such as the US Conservation Reserve Program (CRP) that is administered by the United States Department of Agriculture (USDA) and funded under the Farm Bill, that seek to recover and maintain pheasant populations (Delisle and Savidge 1997; Matthews, Taylor, and Powell 2012b; Murray and Best 2003; Patterson and Best 1996). One CRP program in Iowa, referred to as CRP SAFE, encourages farmers to grow perennial grasses on parts of their land to provide pheasant habitat (Iowa Department of Natural Resources 2013) via yearly rental payments to the farmers. It has been demonstrated that pheasant populations respond positively when previously agricultural land is managed according to CPR requirements (Hiller et al. 2015; Matthews, Taylor, and Powell 2012a, 2012b; Nielson et al. 2008;). A critical element in maintaining ring-necked pheasant populations is the interspersion of local grassland patches within landscapes containing small grains and row crop agriculture, and this is a requirement of the CRP (Jorgensen et al. 2014). Additionally, CRP management requires maintaining grass-like habitat (small grains and perennial grasses), which serve as breeding habitat for pheasants (Jorgensen et al. 2014).

An added economic incentive to landowners to participate in this conservation program, could be that perennial grasses can be harvested as biomass (Florine et al. 2006). Avian nesting habitat is severely limited in agriculturally dominated landscapes in the Midwestern US (Patterson and Best 1996; Warner 1994). Traditional row crops can provide some cover, at least until the field is disturbed by harvest (Burger, Dailey, and Schulz 1994). Unlike traditional row crops (e.g., corn), perennial grasses not only provide nesting habitat, but harvesting can also be delayed so as not to disturb the nesting season for most wildlife species, including pheasants (Murray and Best 2003). It has been suggested that leaving standing biomass over winter provides important wildlife cover and seed forage. Postponing harvest until later in a season does not come without consequences; there is a peak window in which to harvest biomass feedstocks, such as perennial grasses, and delays past that period result in degradation of biomass (Gamble et al. 2015). 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 earlier. When considering trade-offs inherent in managing landscapes where biomass harvesting and pheasant harvesting (i.e., hunting) both take place, we expect to see a trade-off between

biomass yield and pheasant abundance (e.g., if biomass yield increases then pheasant population size will decrease and vice versa). We expect this because biomass harvesting disturbs pheasants but delaying biomass harvest so not to disrupt the pheasant life process allows that biomass to degrade.

The complex interactions between individuals present in these multifunctional agricultural landscapes makes this a situation ideal for employing an agent-based model (ABM). ABMs have been used to understand how populations respond to landscape heterogeneity with species as varied as red-cockaded woodpeckers (Schiegg et al. 2005), tigers (Carter et al. 2015), and wood mice (Liu et al. 2013). We developed an ABM that model pheasants, vegetation, hunters, and tractors in various agricultural landscapes and a set of four time-based scenarios to investigate trade-offs between pheasant population size and biomass yield. Landscape composition and size affect agricultural yield (Beckman et al. 2019; Martin et al. 2019), profitability (Brandes et al. 2016; Polasky et al. 2008), and wildlife (Beckmann et al 2019; Polasky et al. 2008; Brandt et al. 2014). We test all scenarios across four different landscapes to examine how landscape composition impacts model outputs. We expect that landscapes with more crops and CRP land will have higher pheasant populations overall because these lands are harvestable and do an adequate job of providing some habitat to pheasants (Behrman et al. 2015; Delisle et al. 1997; Hiller et al. 2015; King et al. 1995; Matthews et al. 2012a; McCoy et al. 1999; Nielson et al. 2008; Patterson et al. 1996). The question arises in determining how harvest timing will affect pheasant populations givens tractors ability to kill pheasants.

The goal of this study is to assess the effect of various temporal harvest strategies on biomass yield, pheasant harvest, and average pheasant population size over a 5-year period, and to investigate how landscape-design impacts the outcomes of such strategies. We are also interested in how scenario outcomes compare in economic terms, including appropriate valuation of ecosystem services, which includes provision of biomass for energy and provision of game. It is important to understand the dynamics of complex field-scale interactions between multiple agents both for developing better management practices and ensuring optimal outcomes.

2. Materials and methods

2.1. Study area

A selection of agricultural fields in Iowa, USA were chosen as the base landscape for this analysis. The simulated area meets CRP SAFE requirements 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 Antares project is a multi-lab and -university project sponsored by the Bioenergy Technologies Office of the US Department of Energy that seeks to create a comprehensive landscape design handbook for bioenergy production in Iowa. The study region represents a typical agricultural area in Iowa. Most land is used to grow corn and soybeans with some patches of deciduous forests, wetlands (herbaceous and woody), hay, alfalfa, oats, and grasslands interspersed on the landscape. 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 (8.09 ha) and no larger than 160 acres (64.75 ha) 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 (Natural Resources Conservation Service 2017). Establishing winter cover and a nearby food plot is key to ensuring that pheasants survive through the winter (Weigand et al. 1976).

The winter cover protects pheasants from predation and cold temperatures, while the food plot ensures they can access enough high caloric food to survive the cold. Nests and broods have greater chances of survival if adequate nesting cover is provided and left undisturbed until hens have finished nesting and brooding (Baxter et al. 1973; Camp et al. 1994; Clark et al. 1999).

This area is normally managed for corn and soybean. Typically, corn planting in Iowa begins in April and continues through June, with harvest commencing in mid-September and finishing by mid-November (Daughtry et al. 2006).

2.2. Model description

The model description follows the Overview, Design concepts, Details (ODD) protocol for describing agent-based models as laid out by (Grimm et al. 2020). The model was implemented in NetLogo version 6.0.4 (Wilensky 2016).

2.2.1. Purpose and patterns

This model was designed for theoretical exposition and investigation of ring-necked pheasant population dynamics in an agricultural landscape that includes bioenergy crops. Specifically, this model was designed to evaluate the effects of harvesting biomass and hunting on ring-necked pheasant populations on hypothetical landscapes.

To evaluate our model, we reproduce three separate patterns: population dynamics, habitat usage, and hunting trends. The first pattern, pheasant populations dynamics, is distinctive seasonal cycles of population boom-and-bust. Relatedly, pheasant's use of habitat is seasonal and predictable. This gives rise to the second pattern: pheasant habitat usage. We ran the model with no tractors or hunters on the landscape for 25 years to ensure that pheasant population dynamics mirrored field observations. Beginning with an initial population of 50, the model exhibited a stable pheasant population. When compared to 36 years of pheasant data from Nebraska, the population dynamics produced by the model fit the overall pattern of pheasant counts and the seasonality captured by the data and is reflected in our population results (Williams, Ives, and Applegate 2003). Additionally, demographic data from a 5 year field study in Iowa followed trends of our model output (Clark, Bogenschutz, and Tessin 2008). Specifically, the boom and bust nature of pheasant populations was well-captured in the model, with populations increasing in the spring during the reproductive season and then steadily declining over the year until spring the next year. During these baseline model simulations, pheasant seasonal use of habitat was documented. In examining field data, hens preference for grassland, and occasional use of woody habitat, over the years was confirmed (Schmitz and Clark 1999; Perkins et al. 1997). Winter and nesting season are the two periods during the pheasant life cycle when habitat is especially important. During winter, pheasants tended to prefer grassy, woody habitat, and habitat that provided adequate cover (Perkins et al. 1997). For the nesting season, hens will nest in many types of habitat (e.g. grassland, pasture, fence line), though our percent of habitat used for nesting was similar to field data (Clark, Schmitz, and Bogenschutz 1999). Finally, the last pattern is the average amount of pheasants that are hunted each season. We examined 17 years of pheasant hunting data from Iowa (Fritzell et al. 2018) to determine how well our model was able to reproduce hunting patterns. Overall, the hunting data produced by our model was typically within range of the Iowa hunting data (Figure 1). The

variability of the observed hunting data arises in part from the fluctuation of hunters each season, which can be influenced by a myriad of external factors such as shifting national demographics or depressed economic growth (U.S. Department of the Interior et al. 2016). Our modeled results are within an order of magnitude of the observed hunting data.

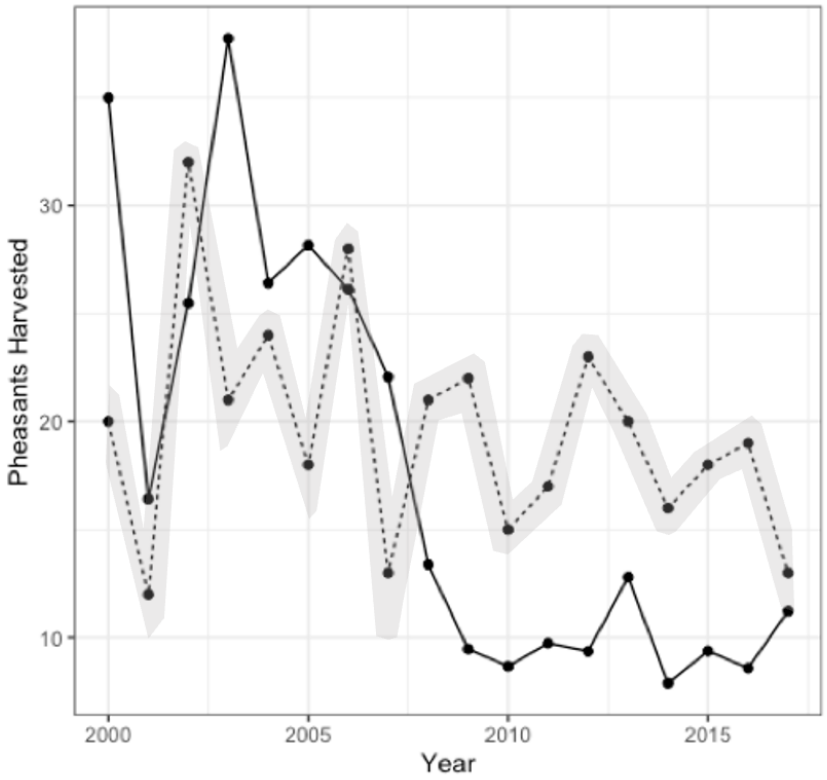

Figure 1. Simulation results averaged across 50 replicates (dashed line, grey region is standard deviation) compared to observed pheasant hunting data from Iowa 2000-2017 (solid line).

2.2.2. Entities, state variables, and scales

This model has four entities: pheasants (both male and female), tractors, hunters, and vegetation. All state variables characterizing these entities are listed in Table 1.

174 ***Table 1. All entities with descriptions of the state variables and corresponding values.***

Variable	Description	Value(s)
Pheasant Entity		
energy	Total mass (kg) of individual pheasant	[0,inf); female average is 0.8 kg, male average is 1.95
age	Age (in days) of pheasant	[0, 1095]
food-trials	Trial number of attempts to find food per day	[0, 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?	Whether the pheasant has established territory for mating	True/false
terr-size	Area (in cells) of mating territory	0 U [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 las laid	[7,15]
(x, y)	Location (cell number in coordinate system) of pheasant	([0, 175], [0, 120])
Tractor Entity		
bio-yield	The amount of biomass a tractor can harvest (dry ton/km^2)	[0, inf)
corn-yield	The amount of corn a tractor can harvest (dry ton/km^2)	[0, inf)

(x, y)	Location (cell number in coordinate system) of tractor	([0, 175], [0, 120])
	Hunter Entity	
target	Identifies the 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, inf)
(x, y)	Location (cell number in coordinate system) of hunter	([0, 175], [0, 120])
	Vegetation	
owner	Current male pheasant that is claiming ownership of patch in attempt to form a harem	Male pheasant ID
patch-harem-num	Identifies all the patches that belong to one harem	Male pheasant ID
nest?	Whether pheasants can nest in this vegetation type	True/false
luse	Type of land use on a patch	Alfalfa, hay, soybean, grass/shrubland, woody wetland, herbaceous wetland, forest, corn, switchgrass (counted towards CRP), CRP food plot.
food	Amount of food provided to pheasants by vegetation (crude protein)	Crop specific, variable over time
cover	Amount of cover (*c*) provided to pheasants by vegetation, plant height (m)	Crop specific, variable over time
biomass	Amount of potential biomass yield that is available for harvest by tractors	Crop specific, variable over time

harvestable?	Whether the vegetation type may be harvested for biomass	True/false
been-moved?	Whether a patch has been harvested (by tractor) for the current season	True/false

Both female and male pheasants have attributes that are state variables in the model. These include age (days), mass (in kg), the number of attempts at acquiring food in a day, whether or not they have established a territory for mating, the area (in cells) of their territory (set to 0 if they have not established a territory), identity of their mother, the flock they belong to during the winter, and the identity of the nearest pheasants of the same gender (used to help them form flocks). The dynamic state of each female pheasant is tracked by the following variables: the harem she belongs to, whether she has established a nest, the number of eggs she lays in a year, and the location of her nest. Each male pheasant has state variables describing his desirability to females, the number of attempts to attract females (lekking behavior), whether he has established a harem, and the area (in cells) of his harem (set to 0 if he has not established a harem).

The dynamic state of tractors is tracked by variables that describe the amount of biomass and corn they have harvested (dry ton/km^2). The state of hunters is described by 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 in which they can look for male pheasants to hunt, and the total number of successfully killed roosters. Hunter's accuracy and the radius in which they may look for male pheasants to hunt are randomly assigned. Additionally, hunters may only kill up to three roosters per day, per bag limits in Iowa.

Grid cells (i.e. patches) describe the landscape composition. The dynamic value of patches are recorded via state variables that describe the amount of energy provided to pheasants if consumed (measured in percent crude protein), the amount of cover provided to pheasants (simulated as plant height in meters), the amount of potential biomass yield to be harvested (dry ton/km^2), and Boolean variables that represents whether pheasants are allowed to nest in the specific type of vegetation and whether that vegetation is eligible for harvest by tractor. Other landscape variables detail individual patches interactions with pheasants and tractors and are outlined in Table 1. The state of each patch varies with the season.

Multiple landscapes are simulated, and a detailed description of each can be found in Section 2.4 Experimental Design. Each landscape is approximately 5 km^2 because this is roughly equal to the home range of a ring-necked pheasant (Jorgensen et al.2014). The world is represented by 120 x 175 patches; thus, each patch is approximately 270 m^2. Model space is bounded meaning that pheasants at one edge of the space cannot jump to cells on the opposite edge. One time step represents one day, and simulations were run for 5 years.

2.2.3. Process overview and scheduling

This model simulates multiple processes (Figure 2) at the field scale. Pheasants engage in seven processes that concern key aspects of the pheasant life cycle—feeding, reproducing, surviving, and selecting habitat. Activities related to reproduction and parenting are described in detail in the Submodels section. Hunters and tractors have one process each, hunting and harvesting respectively. Finally, there is a process related to the update of the environment and habitat conditions.

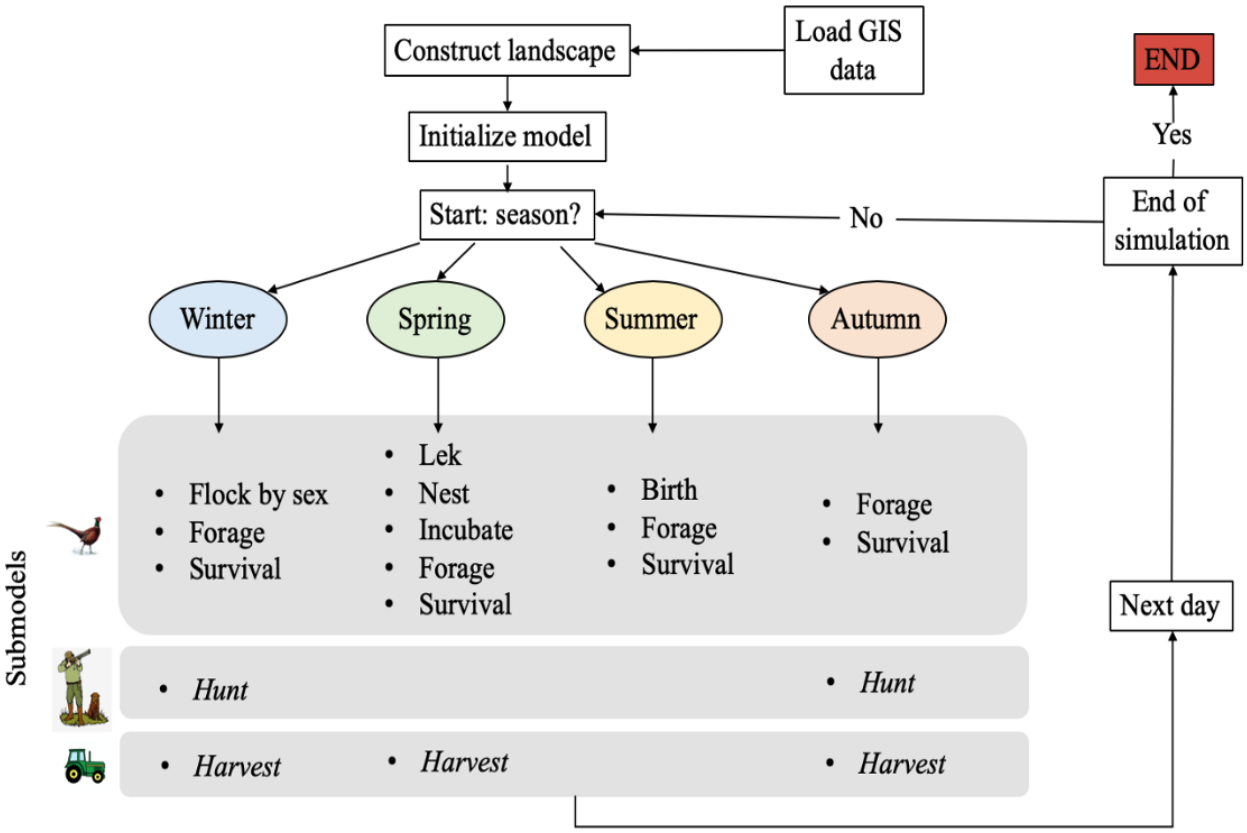

Figure 2. Diagram of ABM scheduling, italicized submodels represent operation that may change time of execution depending on the analysis being run.

Seasons determine which submodels are executed in the model, because pheasant life cycles and harvesting are time dependent. First, all input data are 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, then time will advance, and the cycle will begin again. The model will continue to run until the designated stop time. Seasons are defined as follows: Winter (December 1 – February 28), Spring (March 1 – May 31), Summer (June 1 – August 31), and Autumn (September 1 – November 30).

2.2.4. Design concepts

2.2.4.1. Basic principles

This model seeks to recreate system dynamics for the purpose of prediction and evaluation. Specifically, the model recreates agent's behaviors and the interactions that occur between agents with the purpose of being able to evaluate changes to the system. Agents follow heuristic rules for various procedures, thus the basic principles are implemented in the submodels. Using an ABM for scenario evaluation has been used in many instances spanning wide topics such as evaluating COVID-19 transmission risks in facilities (Cuevas 2020), logistic decisions in freight transport (Schroeder et al. 2012), and evaluating the impact of off-hour deliveries (Mommens et al. 2018). In this study, the model is replicating pheasant lifecycle process on an agricultural field that also has tractors harvesting crops and hunters hunting pheasants. Ring-necked pheasant life history stages and processes, hunting processes, harvesting processes, and vegetation growth form the basis of the modeling framework. Geotagged tractor paths from various fields in Iowa [personal communication with Mike Griffel (Idaho National Laboratory) on February 7, 2019] informed the biomass harvesting simulations. Hunter behavior is modeled after hunter testimonials and how-to guides (Iowa Department of Natural Resources 2000, 2013).

2.2.4.2. Emergences

Key outputs from the model—which are later used in calculating ecological valuation—are modeled as emerging from the behavior of agents, specifically pheasants, hunters, and tractors. Key outputs are total biomass and corn harvested from fields and pheasant mortality, values and causes. Harvest values are dependent on tractor actions and varied temporally in the model. Pheasant population dynamics are subject to many processes in the model; however, mortality causes and numbers are emergent results that vary according to hunter and tractor behavior explicitly when these agents are on the landscape executing their main functions (seen in Figure 2, *hunt* and *harvest*).

The environment impacts emergent results and provides some imposed results in the model. In terms of emergent results, pheasant use of habitat, and the quality of that habitat, will impact their life processes. Imposed results arise because the state of each patch varies with the season. To account for this, the food, cover, and biomass of certain vegetation types are presented as time-dependent functions. We gathered data from the literature regarding these three attributes for vegetation types simulated by the model, and then constructed functions that represent these processes over the year. The food parameter for vegetation is represented as percent crude protein and shown in Figures 3 and 4. We represent the cover provided by vegetation structure, in this instance as the vertical plant height (m), in the model (Figures 3 and 4) to account for the effect that vegetation has on bird survival.

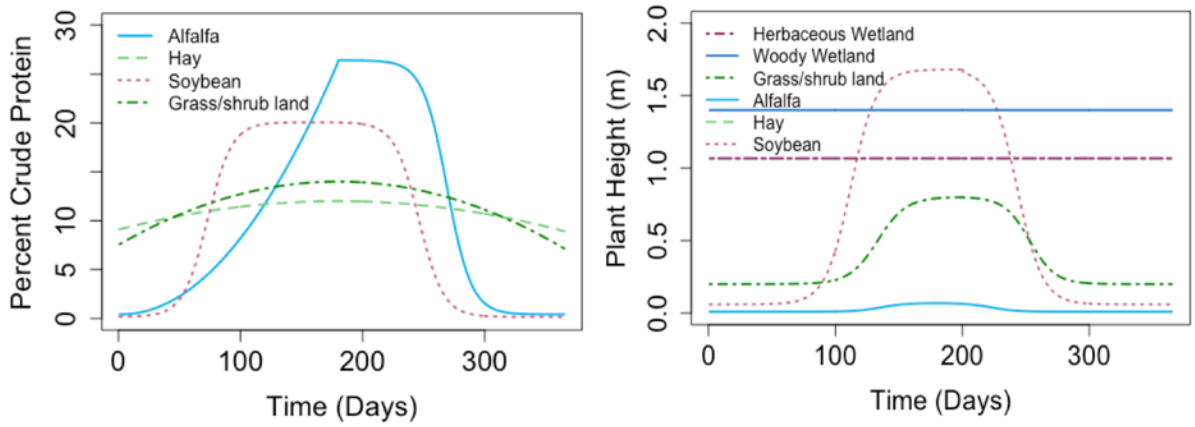

Figure 3. Food provided by land use (left) and cover provided by land use (right), seasonal food and cover values determined from the literature (Banta 2012, Han & Twidwell 2009, Johnson et al.

2019, Kayembe & Rensburg 2013, Mak et al. 2014, Mala & Fadlalla 2013, Montana Natural Heritage Program 2010, Nelson et al. 2016, Sun & Frelich 2011, Yupsanis et al. 2010).

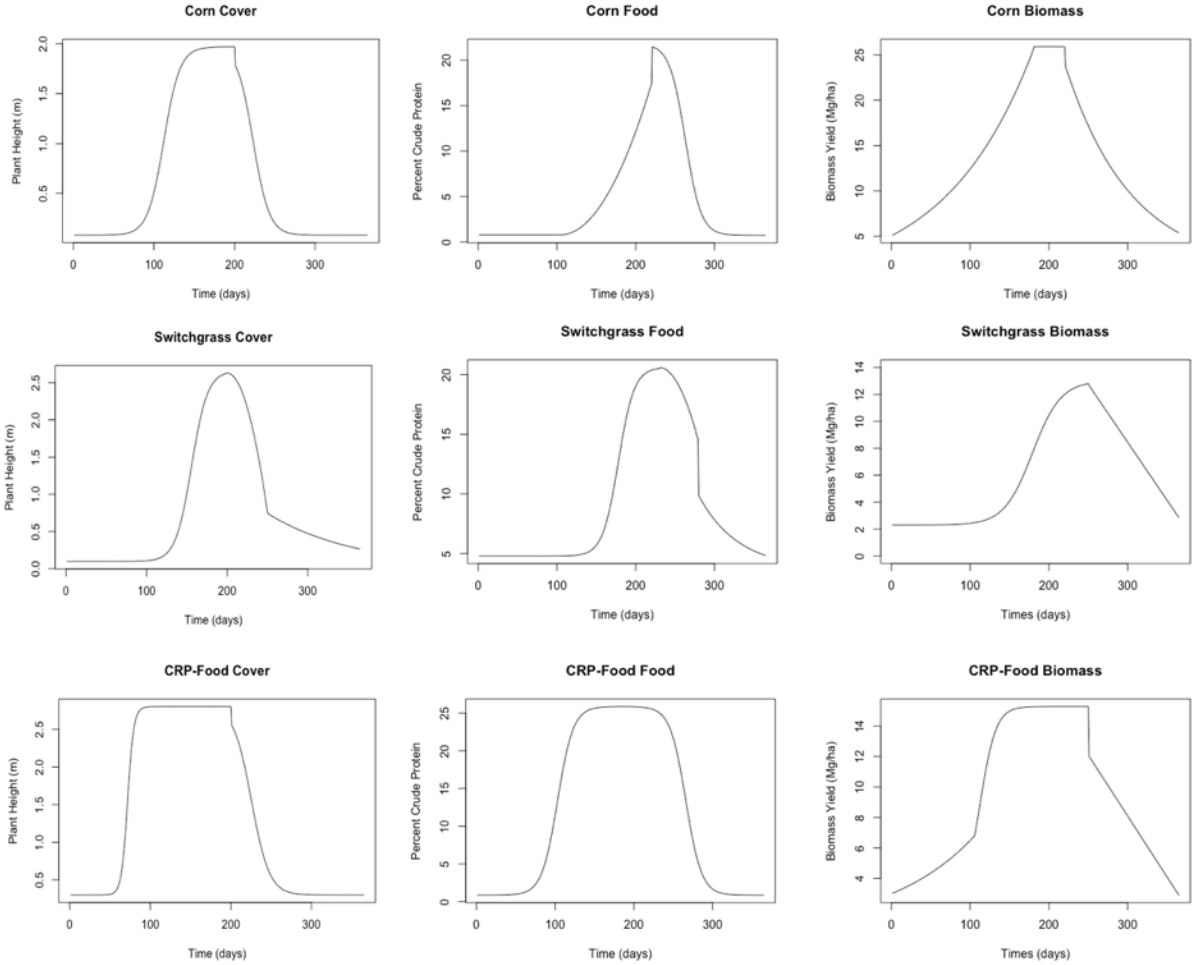

Figure 4. Available cover, food, and biomass (left to right), for corn, switchgrass (CRP), and CRP food plot (top to bottom) (Ashworth et al. 2017, Li & Sun 2016, VanLoocke et al. 2012, Zhang et al. 2015, Zhao et al. 2003).

Both types of CRP lands (switchgrass and food plot) are eligible for harvesting. Additionally, we simulate corn harvest because Iowa is the largest producer of corn in the country (US Department of Agriculture 2017) and tractor impact on pheasant populations in corn fields is important to consider. The biomass parameter for these three land uses (Figure 4) is represented as dry ton/km^2.

2.2.4.3. Adaptation

Both pheasants and hunters have some form of adaptive behavior. Pheasants exhibit the most type of this behavior through their reproductive processes, winter flocking, and in response to other agents. During the reproductive season, female pheasants choose males to reproduce with, based in part on their desirability, and move towards their mate. 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. When flocking for winter, pheasants will search for other pheasants of the same sex and then move towards them. Finally, pheasants will move away from tractors when moving around the field, with one exception (discussed in Submodels). In all these instances, pheasants are changing their (x, y) location based on other agents' location. This movement is based solely on the objective of moving towards (other pheasants) or away (tractors). When hunting, hunters may make movement decisions based on the presence of roosters. Without a target, hunters are actively seeking out roosters by moving through the field in one cardinal direction. For both pheasants and hunters, when executing movement decisions, the first agent that satisfies the current objective is used and no other searching is done.

2.2.4.4. Objectives

During the reproductive processes (Lek, Nest, Incubate), the objective of a pheasant is to mate and successfully reproduce. Success at each of these separate activities is measured differently. During the "Lek" submodel, the goal of male pheasants is to establish a harem. Similarly, during the "Nest" submodel, the goal of female pheasants is to establish a nest. Finally, female pheasants are aiming to finish the "Incubate" period with an intact nest. During this period, they do not travel as far when foraging and will not flee an approaching tractor. While flocking during winter, pheasant's objective is to find other pheasants of the same sex and habitat with appropriate winter cover. At all times are pheasants attempting to avoid tractors when executing movement on the landscape. All in all, pheasant forage behavior and territory decisions are based on surrounding vegetation and other agent's locations.

A hunter's objective is to kill as many male pheasants (roosters) as possible given the daily limit of a haul. This objective is affected by how many hunt trials a hunter has remaining for that day, and how many roosters may be in their vicinity. See "Hunt" submodel for a detailed description of how hunting is executed. The *accuracy* of a hunter is included to simulate hunter's skill because this has a direct impact on whether a hunter will be successful.

2.2.4.5. Sensing

Pheasants can sense the gender and the mating status of other pheasants within their search radius. This information drives movement and mating. They can also sense whether adjacent patches are occupied by other agents and the vegetation type there which also drives movement decisions. 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.

2.2.4.6. Interaction

All interactions between agents in the model occur during one day (i.e., timestep).

Pheasants

When foraging, pheasants interact directly with the landscape by acquiring food (see Emergence for details on vegetation-specific food). This process occurs on the local scale, since pheasants are not allowed to exceed a specific search radius (more details, Forage submodel).

During the lekking process, three kinds of interactions are occurring: between males and females, among male pheasants, and between male pheasants and the landscape. Male pheasants interact directly with female pheasants by having them join his harem if all requirements are met (see "Lek" submodel for more details). Male pheasants are competing with other male pheasants for female pheasants. When a male pheasant successfully establishes a harem, that territory and those female pheasants are no longer available for other male pheasants. Lastly, when a harem is successfully established, the male pheasant directly takes "ownership" of the landscape patch (*patch-harem-num* changes). All interactions are local because male pheasants may only execute these processes within a specified harem radius and within a specified number of trials.

Similar to the interaction between a male pheasant and the landscape patch he "owns" as part of his harem, female pheasants also directly take ownership of landscape patches within a harem when establishing a nest. Also, when a female successfully establishes a nest, that patch is no longer available to other females in the harem, illustrating a mediated interaction.

The last kind of pheasant to pheasant interaction occurs during winter when they flock with pheasants of the same sex. This is a direct action that occurs on the local scale; pheasants use a small search radius to attempt to find other pheasants.

Hunters

When executing the hunt procedure, hunters experience two types of interaction. Firstly, hunters interact directly with pheasants by killing them. This is a local interaction that is defined by the hunter's search radius. Second, hunters are competing with each other for roosters which are a limited resource. This mediated interaction is global because the model is at the field scale and there is a set number of roosters in the field.

Tractors

Tractors engage in two types of interactions, one with the landscape and one with pheasants. When executing the harvest submodel, tractors directly interact with the landscape by removing biomass from patches that they occupy. This is a global interaction as there is no radius in which a tractor must stay—the entire field is eligible for mowing given vegetation-specific constraints (see Emergence and Harvest submodel). While harvesting the landscape, if a tractor comes across a pheasant, the tractor will kill that pheasant directly.

2.2.4.7. Stochasticity

There are many stochastic events in this model. Whenever any entity (agent or patch) executes a procedure, the order in which the agents 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.

Let *X* be a decision made with probability *p*. Each time decision *X* is to be made, the uniform distribution U[0, 1] is sampled to generate $y \in \mathbb{R}$. The event *X* occurs if $y \leq p$ and does not occur otherwise.

Each individual is selected randomly with probability 50% of completing the following procedures on any given day, depending on their sex or lifestage.

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

2.2.4.8. Collectives

The only collective that exists in this model occurs when pheasants flock by sex during winter. This is an emergent property of pheasants because the flocks that arise are a result of movement rules (submodel "Flock by sex"). This collective is not explicitly represented in the model.

2.2.4.9. Observation

At each time step, we record the pheasant population size (both female and male counts), the current day, week, and year. When tractors are active on the landscape, we keep track of the total biomass yield that is harvested (dry tons/km^2). When hunters are active on the landscape, we track the cumulative pheasants killed by hunter (count).

2.2.5. Initialization

The model begins on January 1 of year 1. Initially, 40 pheasants (20 male and 20 female) are randomly placed in patches on the landscape, given the 5 km^2 area (Houts, Price, and Applegate 2002). Each pheasant is assigned an age, energy, and desirability (males only) stochastically upon creation (Table 1). All state variables for pheasant and landscape entities are initialized during the set-up procedure. Hunters and tractors are initialized when the Hunt and Biomass Harvest or Corn Harvest submodels are executed, respectively. All entities, except hatchlings, are placed randomly on the landscape when initialized. Hatchlings are placed near their mother (submodel "Birth").

The landscape of this model is initialized by importing GIS land data; however, this data only defines the extent of the study area and the static spatial distribution of land use categories. Land data represents existing farm fields in Iowa, both the typical types of vegetation present and their general distribution. The environment consists of 120 x 175 cells of approximately 270 m^2. Possible land uses include Alfalfa, hay, soybean, grass/shrubland, woody wetland, herbaceous wetland, forest, corn, switchgrass (counted towards CRP), and CRP food plot. 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 land use (Table 1 and Emergence).

2.2.6. Inupt data

The model does not use input data to represent time-varying processes.

2.2.7. Submodels

The submodels of the ABM are described here in detail.

2.2.7.1. 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 their trials to find food, they will continue to search for food. Pheasants are allowed 4 trials and not allowed to exceed an activity radius of 0.25 km (Hanson and Progulske 1973). If the pheasant's current patch location has food (denoted by patch variable food), the pheasant will increase their energy level by consuming the available food on that patch. The patch variable energy will decrease by the equivalent amount. Pheasants will than choose a random heading and move forward a random amount that depends on the amount of energy they have to move.

After spring, female pheasants rear their broods. 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 (Farris et al. 1977). Even though young chicks 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. Therefore, if an individual pheasant is a juvenile ($age \leq 77$ days), then it must stay within 100 m of its mother (Riley et al. 1998). If a juvenile is further from its mother than the threshold, it will move towards her.

2.2.7.2. Lek

In March, males begin to establish crowing grounds. These are areas where they lek or display various courtship behaviors 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.

Thus, this procedure is executed by male pheasants only. Males are allowed two attempts to establish a harem. If they are unable to establish a harem within the two trials, 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. Each male also has a *harem-radius* (measured in patches) which describes how large an area each male may search during a given time step to establish a harem. The radius of that circular area is given by multiplying a male's *desirability* value by 20 to ensure that crowing territories stay within appropriate bounds of possible size (Farris, Klonglan, and Nomsen 1977).

During a lekking trial, each male will check the patches that occur within his harem-radius for ownership by other males and whether the vegetation is suitable for nesting. If all

requirements are met, then five things will happen. First, the male pheasant will set their parameter determining whether they are able to establish mating territory to TRUE to indicate that they are in the process of moving through the reproductive cycle. Second, every patch within the harem radius will change owner from `nobody' to the ID of that particular male. The patches will also set patch-harem-num to the ID of the male owner. Next, each male will set his territory size to the number of patches within his 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 territory parameter to true, set territory size as that of the male, and set harem-num to the ID of the male owner. If a female is within the breeding territory of more than one male, 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 trials, territory parameter will remain FALSE and they will not participate in reproductive activities for the season.

2.2.7.3. Nest

Nesting can begin as early as March in southern Iowa, but egg laying usually begins in mid to late April (Tesky 1995). Only hens take part in nesting. After constructing a nest, a hen lays 7 to 15 eggs, often 10 to 12 (Bent 1932). Hens lay one egg per day until the clutch is complete, and then incubation begins. This procedure is executed by female pheasants who belong to a harem 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. 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 lay is randomly chosen. Females will continue to execute this procedure until either the nesting period ends, or they establish a nest.

2.2.7.4. Incubate

Peak incubation occurs in May (Farris, Klonglan, and Nomsen 1977), and hens incubate eggs for 23 to 25 days (Bent 1932). This procedure is only executed by female pheasants who have established a nest and laid eggs. 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 through the entire incubation period. Additionally, while executing this procedure, female pheasants suspend their tractor avoidance behavior. Female pheasants have been known to remain with their nests, even in the face of imminent mortal danger (Bent 1932).

2.2.7.5. Birth

This procedure is only executed by female pheasants who have established a nest and laid eggs. Female pheasants will execute the "Birth" process at some point during the hatching period (see Stochasticity). When "Birth" is initiated, each egg within a hen's nest will hatch in the same timestep (i.e. day). There is a 50% that each hatchling will be female. Each new pheasant, depending on its sex, is initialized with the appropriate parameters (Table 1) and within the mother's harem territory.

2.2.7.6. Check Death

This procedure is executed by both male and female pheasants. The baseline daily risk of mortality is determined based on the pheasants age and relation to their mother if a juvenile. 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 (Penrod et al. 1986). Thus, there is a 0.05 probability of the death of a juvenile with a mother, and a 0.069 probability of death of a juvenile whose mother has died or abandoned them to die (Riley et al. 1998). Adults die with probability 0.021 (Penrod, Austin, and Hill 1986), and senior adult pheasants (older than 2 years) die with probability 0.088 (Riley and Schulz 2001). However, vegetation may provide some cover to pheasants which could reduce their risk of mortality. The daily mortality risk for pheasants (Figure 5), decreases in patches with higher cover because increased vegetation decreases rate of predation (Little, Hockey, and Jansen 2015). 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 their body temperatures high (Weigand et al. 1976).

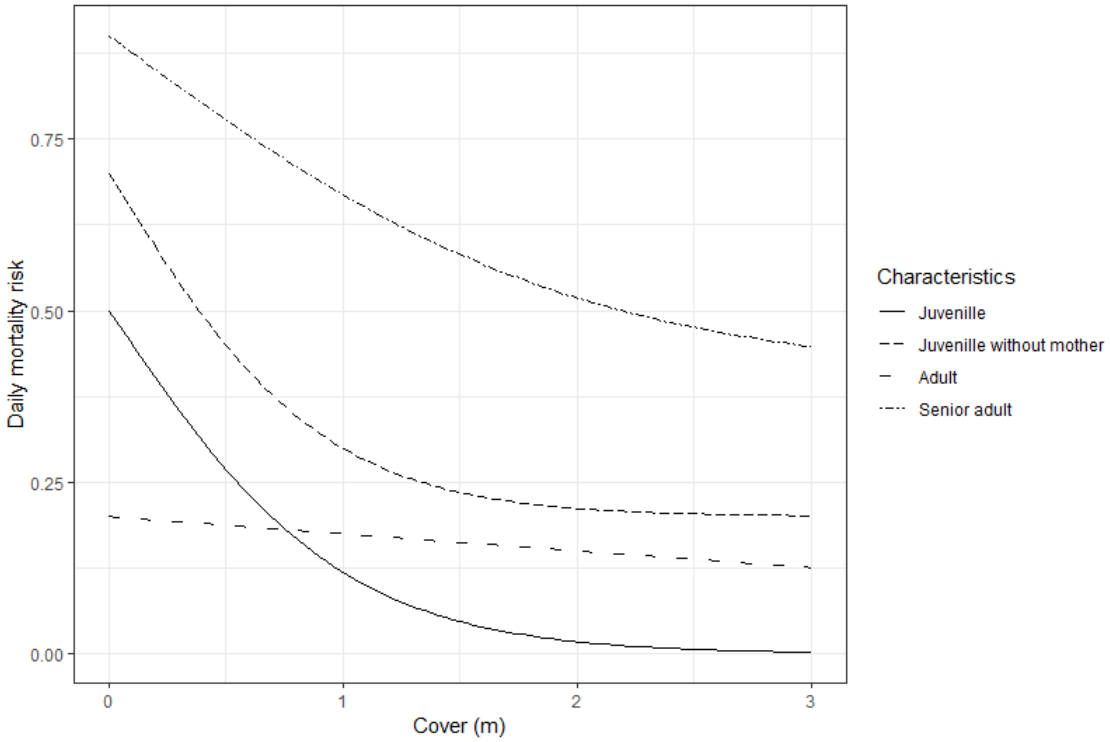

Figure 5. The daily mortality risk (probability of death) for pheasants, given bird-specific characteristics and the cover from vegetation of current patch that the pheasant is occupying. Age ranges are Juvenile (≤ 77 days), Adult (78 days to <2 years), and Senior adult (2+ years).

If the daily mortality risk is greater than a random number between 0 and 1, then the pheasant will execute the "Death" submodel. Otherwise, the pheasant survives. Additionally, if a pheasant's energy reaches zero, then the pheasant dies immediately.

2.2.7.7. 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 and thus be eligible for other pheasants to use in reproduction.

2.2.7.8. Flock by Sex

As winter approaches, broods disperse and pheasants search for winter cover. Suitable winter cover must be close to a winter food source because pheasants will forage only short distances during this season. 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 (Farris, Klonglan, and Nomsen 1977). In this procedure, 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.

2.2.7.9. Hunt

This procedure is executed by hunters. All hunters begin with no hunt trials yet attempted. 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 hunter's 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. 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. If there are no roosters within a hunter's *hunt-distance*, then hunters will check *2*hunt-distance* for roosters. If sensing a rooster within this area, hunters will move forward towards that rooster. Otherwise, hunters will move forward at a random heading within their allowed movement area.

2.2.7.10. Corn Harvest

Tractors execute this procedure by determining if the current patch is corn and then harvesting that corn if the patch has not yet been mown. The tractor then examines the adjacent patches, looking for patches with corn vegetation that have not been mown. Based on this, the tractor will either move forward and harvest or turn right, move forward, and harvest. Tractors mow in straight lines along corn rows, beginning at one side of a field and working across it. If a pheasant is occupying a patch that a tractor is harvesting, then that pheasant will die, and the tractor will continue with its harvesting.

2.2.7.11. Biomass Harvest

This procedure is executed by tractors. First, the tractor will check to see if the current patch is eligible for harvest (vegetation is either switchgrass or CRP food plot) and whether it has been mown. If both criteria are met, the tractor will harvest the current patch. If a pheasant

is occupying this patch, then it will die. The tractor will then examine the parameters of the next patch to determine if it should move to said patch, or a different patch. Tractors emulate the typical harvest practices by mowing the entire boundary of the field and then spiraling inward, to end the mowing patch at the center of the field.

2.3. Experimental design

Simulation experiments were devised to explore the effects of various harvest strategies of both biomass and pheasants. Additionally, we created four different landscapes (Figure 6)—dominated by corn, CRP, grassland, and mixed land uses—to determine how landscape composition affects outcomes from various temporal harvest strategies. Each landscape is approximately 5 km^2, a spatial scale that is biologically relevant to pheasants (Smith, Stewart, and Gates 1999; personal communication with W. Clark June 2017). We averaged 50 replicates simulated for each scenario; each scenario was run on all four landscapes.

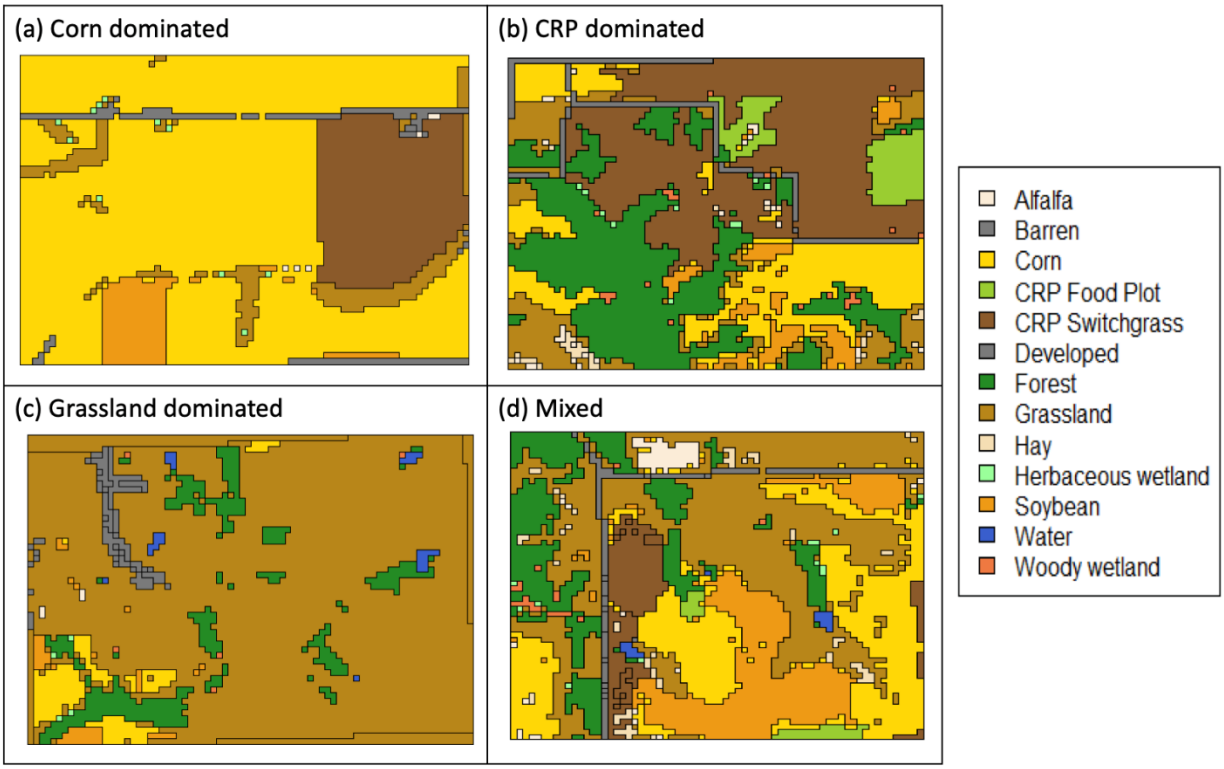

Figure 6. The four landscapes, all approximately 5 km^2, used in the simulation experiments with (a) corn dominated, (b) CRP dominated, (c) grassland dominated, and (d) mixed.

The scenarios (summarized Figure 7) vary biomass harvest timing. Harvest timing was broken into four date ranges: fall (September 2 - October 5), winter (November 10 - December 31), early spring (March 14 - April 16), and late spring (May 1 - May 20) (Gamble et al. 2015; Jungerstodd et al. 2015). The inward-spiral mowing pattern represents the typical way fields with bioenergy crops are mowed, as opposed to back-and-forth row mowing for traditional crops (e.g., corn harvest). The tractor will begin at a point on the outskirt of the field (Figure 7, red point) and mow around the edges of the field, making its way to the center of the field. This is the most common way to mow a

non-corn field for a few 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.

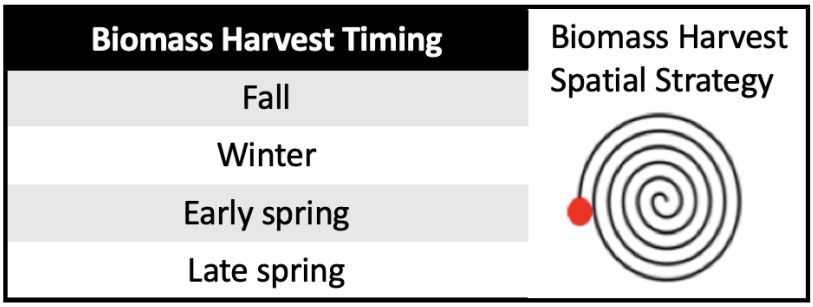

Figure 7. Summary of all scenarios. The described tractor spatial strategy for biomass harvest is illustrated as a figure on the right.

2.4. Experiment execution

Since ABM's are inherently stochastic, we simulated 50 replicates of each scenario consisting of 1) a crop landscape, and 2) a harvest season. This requires running the model 800 times (4 scenarios x 4 land types x 50 replicates = 800) and with one model run taking about 4 hours to compute, it would be time-consuming to simulate all these model runs on a single machine. A common solution to this computationally expensive problem is to use computing clusters to enable parallelization and speed up execution time. We simulated our model in a cluster environment on a high-performance computer. Given these computational constraints, a sensitivity analysis on parameters with natural variability was avoided.

We created our scenarios in Behavior Space, a tool inherent in NetLogo, which allows users to vary model parameters across model simulations. After scenario creation in Behavior Space, we submitted the 16 scenarios to the cluster to be simulated 50 times each. Within this setup, the recorded output includes pheasant population size (male and female breakdown), total harvested biomass, total harvested corn, total number of deaths via tractor (male and female breakdown), and total hunted roosters. Output was recorded approximately every 2 weeks during the 5-year simulation. Annual values were calculated by summing each variable over a simulated year (e.g., day 1 to day 365). To submit the job to the cluster, we used a Portable Batch System (PBS) file developed to simulate agent-based models in parallel (Ponce et al. 2018). This approach : (1) specifies the file path for the ABM, NetLogo, and the setup file, (2) calls the specified setup file, (3) specifies a maximum run-time and number of nodes to use, and (4) includes code for calling a Python script to organize simulation outputs for each parameter combination.

2.5. Ecological valuation

Ecological valuation is the practice of assigning monetary value to an ecosystem and/or its ecosystem services that accounts for the full economic (real or subtextual) value of that ecosystem. This practice has been applied across a diverse range of topics, from assigning value to best management practices like prairie contour stripping (Tyndall et al. 2013) to the environmental impacts of geothermal power projects (Cook et al. 2017). Other studies have assigned monetary

value to species to aid in the conservation of that species (Senzaki et al. 2017) or to ensure a sustainable harvest of that species (Rincon et al. 2016). In this study, we present a valuation approach for pheasant related services, like hunting, in addition to crop yields. Bartkowski (Bartkowski et al. 2017) utilized a similar method in valuing biodiversity. While ecological valuation can be a useful tool for assigning economic value to ecosystems, it is important to be cognizant of the fact that even the direct impacts of wildlife management actions are difficult to quantify, which limits the scope of economic analyses involving wildlife (Anderson et al. 2013).

One area of potential revenue that is difficult to quantify is the social benefit or cultural value of the hunting experience. There is a contingent valuation method, called willingness to pay (WTP), that estimates how much people are willing to pay for an environmental entity or outcome (Wilson et al. 2018). WTP has been used in investigating hunting lease purchase behaviors (Munn et al. 2011, Zhang et al. 2004) and preference of hunt type (Soliño et al. 2017). In lieu of conducting a survey amongst pheasant hunters in Iowa, we varied the amount a hunter would pay for the experience of hunting (*w*) from \$0 to \$1,000 per year.

In assigning potential economic value to our ecosystem, the challenge arises in determining the "worth" of a pheasant, needing to account for all the different revenue streams of the hunting experience; in contrast, accounting for value from agricultural crops is straightforward. In this situation, a pheasant's worth comes solely from its ability to be hunted, because hunters are spending money to hunt pheasants. Considering only this, we define ρ as the sum of travel costs, hotel costs, equipment cost, and license fee paid for by hunters. We assumed a travel cost of \$400 one way, with \$300 airfare or drive expenses and \$100 for incidentals. Given the U.S. federal lodging rate (U.S. General Services Association 2024), we assume a hotel cost of \$100 per night for 5 nights for a total cost of \$500. Finally, we assume that hunters also pay \$100/day for equipment rental and a field access fee. The license fee for an annual pass for a non-resident to hunt pheasant in Iowa is \$144/year (Department of Natural Resources 2020). Thus, ρ is calculated to be \$1,944, which can be thought of as the amount of money that a hunter will pay to hunt pheasants. We multiply this by the number of roosters that are hunted (*r*) minus the number of pheasants deaths due to tractors ($d_m + d_f$) because those pheasants are no longer available for hunting, decreasing the pool of potential targets and representing lost money that could have been reaped had the pheasant been alive. We assume that a third of all male pheasants killed by tractors would have been eligible for hunting ($\delta_m = 0.3$) and that half of the female pheasants killed by tractors may have lain eggs that would hatch male pheasants ($\delta_f = 0.25$). We assumed a price of \$84.45 per dry ton for biomass feedstock (β) (BETO 2016) and a price of \$26.78 per ton for corn feedstock (γ) (Berger et al. 2017). Finally, we calculate the total of each scenario (*EV*) using Equation (1). We multiply the "worth" of a pheasant and WTP by 5 for each of the 5 years that the simulation is run since both ρ and *w* are yearly values. Note that money is not all flowing to a single beneficiary; expenses paid by hunters go to businesses

and community members, license fees go to the state, and profits from agricultural yield go to farmers.

$$EV = 5(\rho + w)\left(r - \delta_m d_m - \delta_f d_f\right) + \beta(h_b) + \gamma(h_c) \quad (1)$$

where,

ρ = "worth" of one pheasant (dollars)

w = willingness to pay (dollars)

r = number of roosters bagged by hunters

d = number of accidental pheasant deaths from tractors, *m* for males and *f* for females

β = price (dollars) per dry ton for biomass feedstock

γ = price (dollars) per ton for corn feedstock

h = amount of harvested feedstock (dry ton), *b* for biomass and *c* for corn

3. Results

3.1. Scenarios

To look at the relationship between pheasant population size and biomass yield, we plotted annual values of these two outputs across all landscapes (Figure 8). The simulation was run for 5 years so each figure displays 5 data points. We encircled all results from a scenario with a curve to highlight the range and potential clustering of results. On the corn-dominated landscape, the scenarios (Figure 8A) display a direct relationship between pheasant population size and biomass yield. The winter harvest scenario has lower reported biomass than the other scenarios which report higher biomass values. The scenarios simulated on the CRP landscape (Figure 8B) exhibit similar clustering behavior as those simulated on the corn landscape. Again, the scenario that simulates biomass harvest in the winter has distinctly lower biomass than biomass yields from other biomass harvest times. However, these low biomass values coincide with high pheasant values which follows expected behavior. The other scenarios on the CRP landscape have higher biomass values and a wide range of pheasant population sizes. On the grass landscape (Figure 8C), we again see lower biomass yield during winter harvest compared to all other scenarios. Similar to the CRP landscape, these lower biomass values are associated with higher pheasant population sizes. Additionally, the other scenarios have higher biomass values but also a wide range of pheasant population values. Finally, we examine the mixed landscape (Figure 8D) and again see that harvesting biomass in winter generated lower biomass values, though the difference is not as wide as on other landscapes. Both spring harvests had lower pheasant values than other scenarios. The mixed landscape is the only landscape to exhibit the kind of trade-offs that we initially expected: lower pheasant population values with higher biomass yield and vice versa.

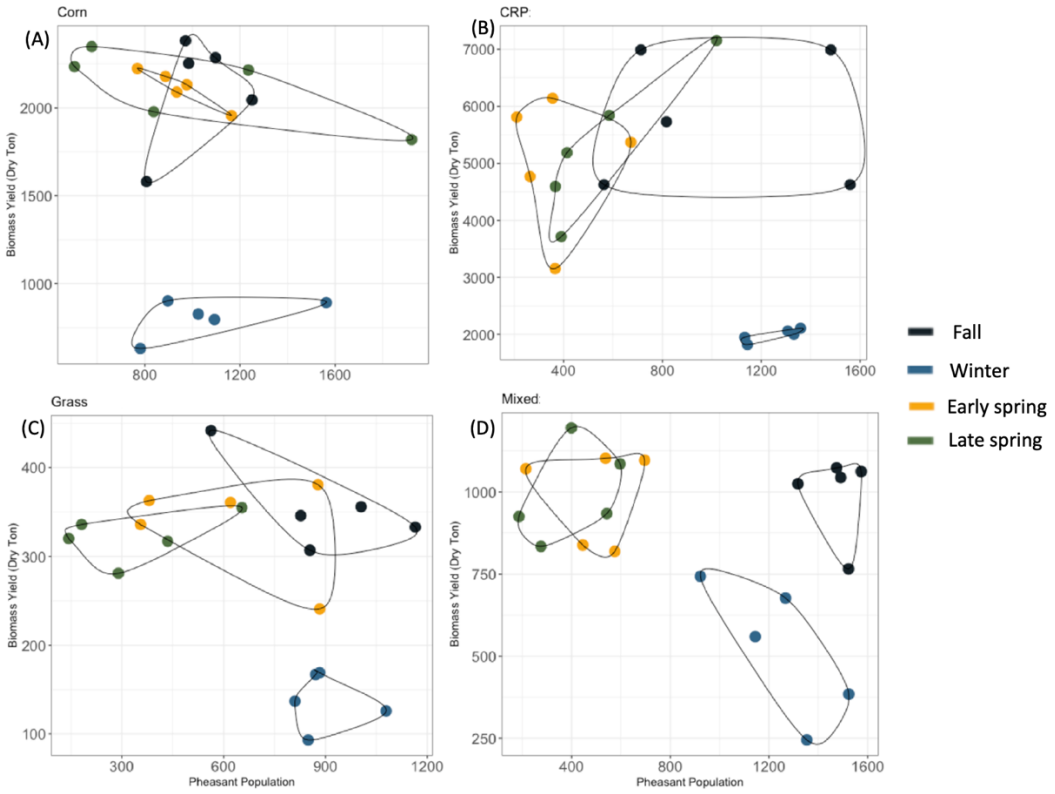

Figure 8. Cumulative annual biomass yield (dry ton) versus cumulative annual pheasant population (number of individuals) for five simulated years for each scenario that is simulated on the (A) corn landscape, (B) CRP landscape, (C) grass landscape, and (D) mixed landscape averaged across 50 replicates. Lines encircle each grouping of scenario values.

We also looked at average annual biomass yield against average annual pheasant population (Figure 9). Error bars in these figures represent the standard deviation among annual biomass yield (vertical bars) and annual pheasant population (horizontal bars). Comparing all scenarios across all landscapes, we see clear indications that biomass yields are lower when harvesting occurs in winter . We also see that harvesting in the fall consistently yielded better outcomes: higher biomass yields and larger pheasant populations than other scenarios.

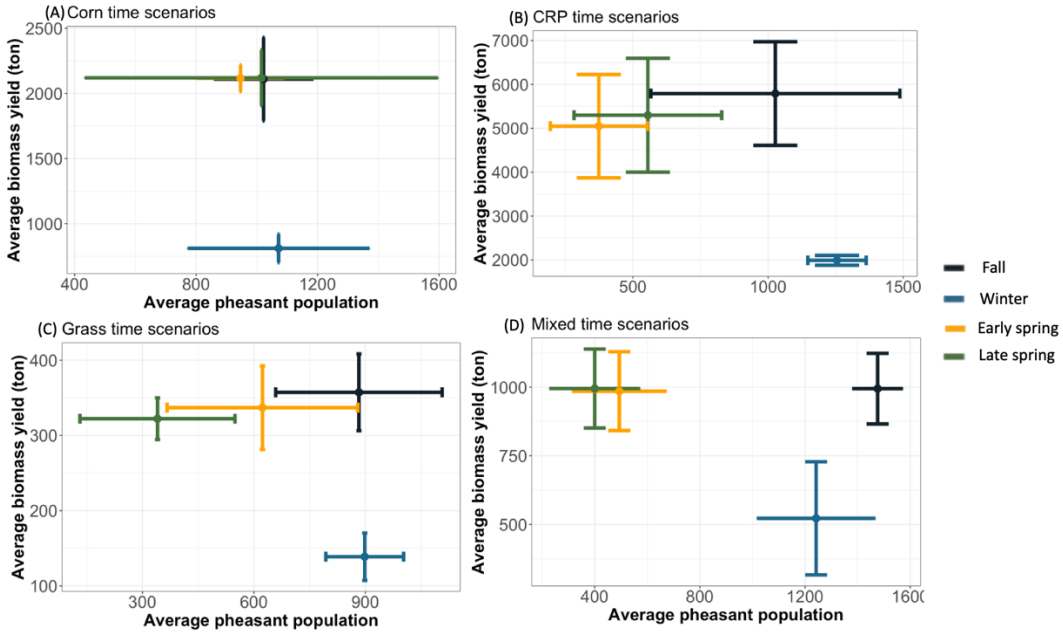

Figure 9. Each figure displays the average biomass yield and average pheasant population size over total simulation time for each scenario. Error bars show variation among annual averages across 50 replicates. Landscapes are (A) corn, (B) CRP, (C) grass, and (D) mixed.

Time series figures display the pheasant population (Figures 10 A,B,C,G) and biomass yield (Figures 10 D, E,F,H) over simulation time (total 5 years). These figures highlight the modeled processes. For example, each of the harvest periods simulated in scenarios with varied harvest timings can be seen as spikes across the simulation (e.g., biomass yield is zero throughout the year expect in winter when harvesting occurs). The cyclic dynamics of the pheasant population abundance is also well illustrated (Figure 10).

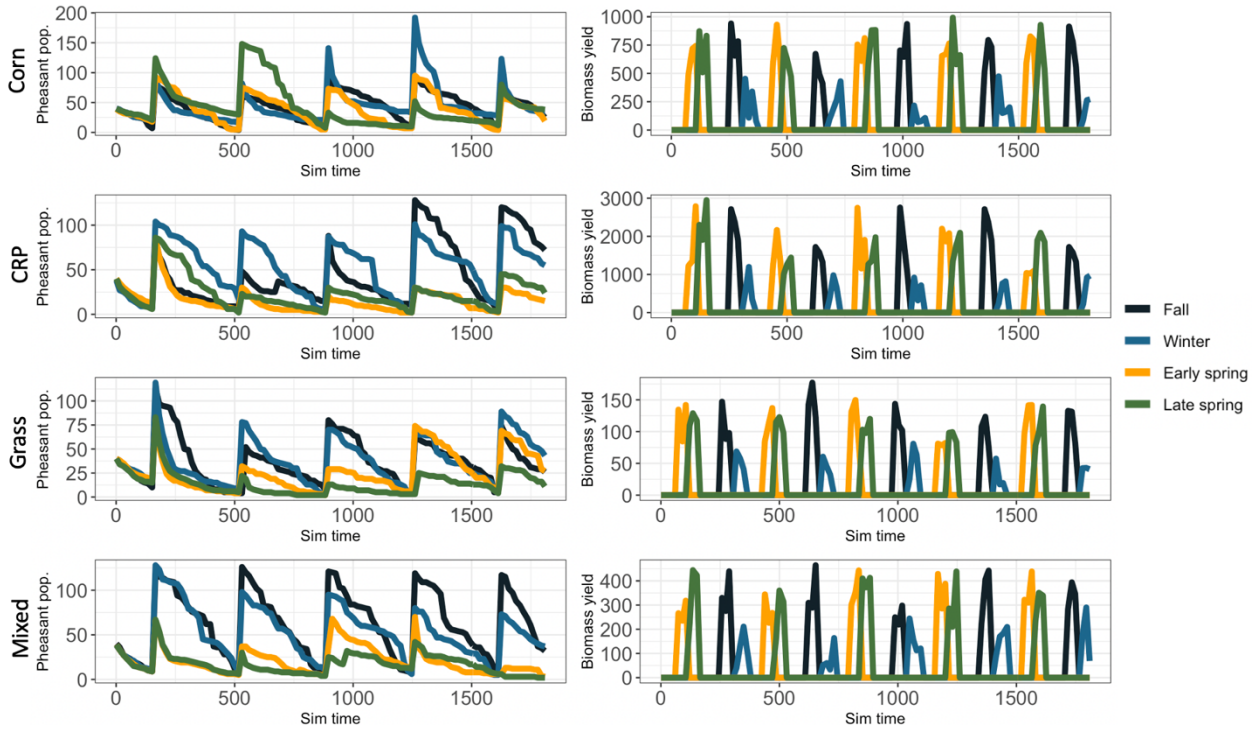

Figure 10. Time series of pheasant populations (individuals, first column) and biomass yield (ton/km², second column). Time series (day) are done for all landscapes (beginning top row corn, CRP, grass, and mixed).

We investigated mortality causes across all scenarios and looked at the number of pheasants (males only) killed by hunters and the number of pheasants killed by tractors broken down by sex (Figure 11). Tractors killed more pheasants than hunters did in these simulations. Across all scenarios on the corn landscape, the maximum number of pheasants killed by tractors was 660 $\pm$ 58.21 compared to a maximum of 272 $\pm$ 31.58 pheasants killed by hunters. Similar results occur on the CRP landscape (502 $\pm$ 29.52 deaths caused by tractors vs. 270 $\pm$ 10.89 deaths caused by hunters), grass landscape (405 $\pm$ 37.23 deaths caused by tractors vs. 266 $\pm$ 23.29 deaths caused by hunters), and mixed landscape (590 $\pm$ 39.07 deaths caused by tractors vs. 241 $\pm$ 26.28 deaths caused by hunters). The number of pheasants killed by hunters were consistent across scenarios and landscapes.

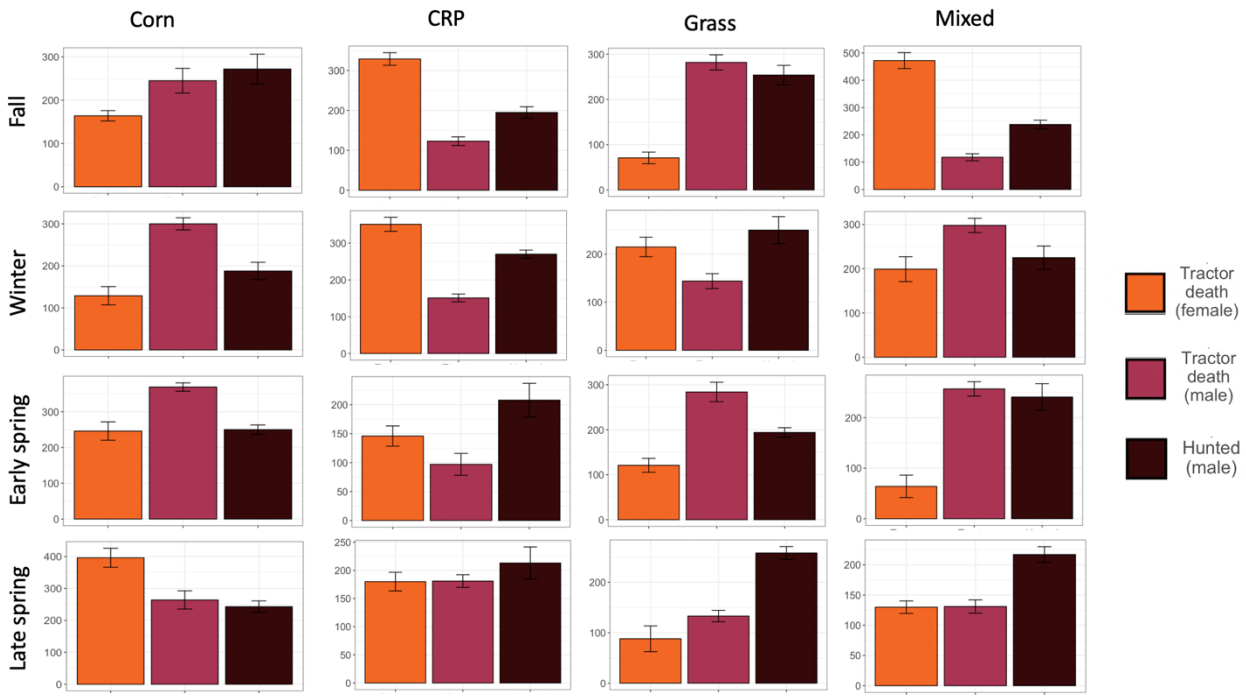

Figure 11. Pheasant mortality via multiple sources displayed by landscape (columns left to right: corn, CRP, grass, mixed) and time scenario (rows top to bottom: fall harvest, winter harvest, early spring harvest, late spring harvest). Simulated sources include tractor death (female pheasants), tractor death (male pheasants), and hunting mortality (males). Error bars represent standard deviation across 50 replicates.

We plotted cumulative and average values with error bars representing variation across replicates for a variety of outputs across all the landscapes (Figure 12). First, we looked at the amount of biomass feedstock produced for bioenergy production. We see a confirmation of our previous finding that biomass values were lower when the harvest occurs in winter for all landscapes. This reflects our simulation of biomass decay over time. Otherwise, the total amount of biomass feedstock was fairly consistent over scenarios that simulated harvest in other seasons. Next, we examined the amount of corn that was harvested. These values should be similar across harvest-scenarios because the time of corn harvest was consistent across scenarios. Finally, we determined the “average pheasant abundance" value for each scenario. The pheasant population sizes varied greatly over time, so “average pheasant abundance" is a better choice for comparing scenarios. Interestingly, populations simulated in corn landscape scenarios showed different dynamics than those simulated in CRP, grass, and mixed landscapes. Average pheasant abundance was similar across all scenarios in corn landscapes. In contrast, on the other landscapes, spring harvests of biomass feedstocks (both early and late) had the lowest average pheasant abundance value while fall and winter harvests had higher average pheasant abundance values.

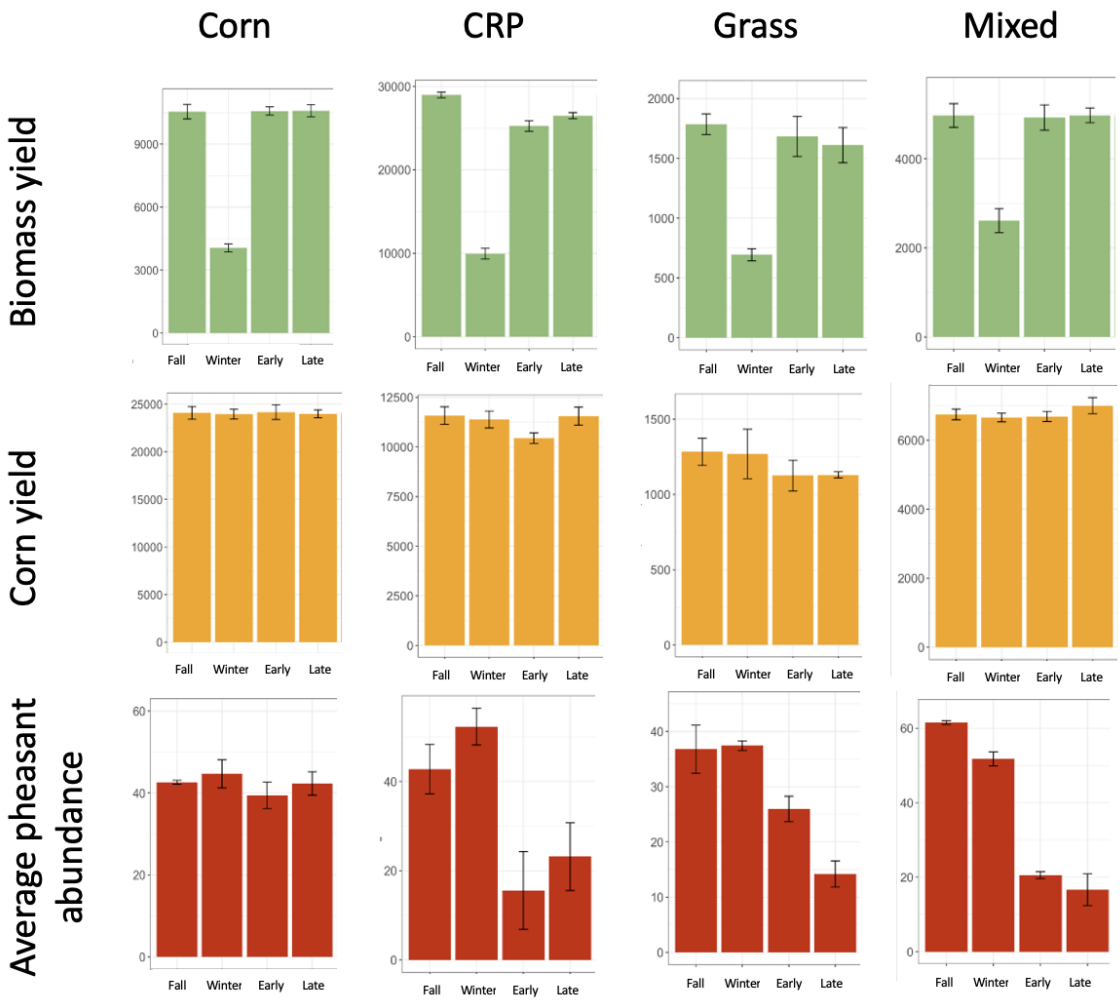

Figure 12. Total biomass yield (ton) (top row) for all scenarios over each landscape, total corn yield (ton) (middle row) for all scenarios over each landscape, and average pheasant abundance (bottom row) for all scenarios over each landscape. Average pheasant abundance for a scenario is calculated by summing pheasant population values over the entire simulation and dividing by the total number of timesteps. Landscapes are corn-dominated (first column), CRP-dominated (second column), grassland-dominated (third column), and mixed (last column). Error bars represent standard error across replicates.

3.2. Ecological Valuation

We calculated the total monetary value associated with each scenario across all landscapes (Table 2). Results of the valuation were sensitive to land cover. Scenarios with the CRP landscape tended to be most valuable with scenarios valued between $2.4 and $3.8 million. The scenarios in corn-dominated landscapes were slightly less valuable, between $1.6 and $3 million. Scenarios in mixed landscapes were valued even slightly less between $1.2 and $2 million. Scenarios with the lowest value ($931,000 – 2 million) were dominated by grasses. Even though values varied across scenarios within a landscape type, total values were fairly similar among scenarios within a landscape. The

monetary value of scenarios with winter harvest tended to be lower than the other scenarios because they consistently reported lower biomass yields than other scenarios.

Table 2. Monetary valuation of each scenario and landscape. Note that these values assume that hunters will not pay (w=0) for the "privilege" of hunting. Abbreviations used in table: C—Corn, R—CRP, G—Grass, M—Mix

Scenario	From pheasants	From biomass	Total
Fall	C: $1,530,900 ± 37	C: $1,529,807 ± 699	C: $3,060,707 ± 495
	R: $737,262 ± 21	R: $2,714,563 ± 249	R: $3,451,825 ± 177
	G: $1,474,038 ± 26	G: $186,810 ± 115	G: $1,660,848 ± 84
	M: $822,312 ± 32	M: $592,709 ± 186	M: $1,415,021 ± 134
Winter	C: $639,090 ± 29	C: $970,467 ± 415	C: $1,609,557± 294
	R: $1,331,154 ± 22	R: $1,150,938 ± 492	R: $2,482,092 ± 348
	G: $1,487,646 ± 32	G: $91,116 ± 185	G: $1,578,762 ± 133
	M: $834,462 ± 36	M: $394,477 ± 182	M: $1,228,939 ± 131
Early spring	C: $756,216 ± 28	C: $1,571,160 ± 705	C: $2,327,376 ± 499
	R: $1,384,128 ± 33	R: $2,435,048 ± 450	R: $3,819,176 ± 319
	G: $763,506 ± 272	G: $168,273 ± 192	G: $931,779 ± 137
	M: $1,437,588 ± 32	M: $580,683 ± 190	M: $2,018,271 ± 136
Late spring	C: $629,856 ± 43	C: $1,524,284 ± 583	C: $2,154,140 ± 414
	R: $1,105,164 ± 28	R: $2,487,404 ± 253	R: $3,592,568 ± 180
	G: $1,906,092 ± 28	G: $166,821 ± 152	G: $2,072,913 ± 109
	M: $1,411,344 ± 18	M: $594,616 ± 200	M: $2,005,960 ± 142

3.2.1. Willingness to pay

We varied hunter's WTP from $0-1,000 when computing the total ecological valuation of each scenario (Figure 13). As hunter's WTP increases, so does the total EV. This is to be expected since as WTP grows, so does the value that pheasant populations bring to the valuation. One unexpected result can be seen when examining the winter and late spring harvest scenarios on corn and grass landscapes. In both instances, the grass landscape is valued below the corn landscape and then between $250 and $500 WTP (winter) and $500 and $750 WTP (late spring) an inflection point is crossed and the grass landscape becomes more valuable than the corn landscape.

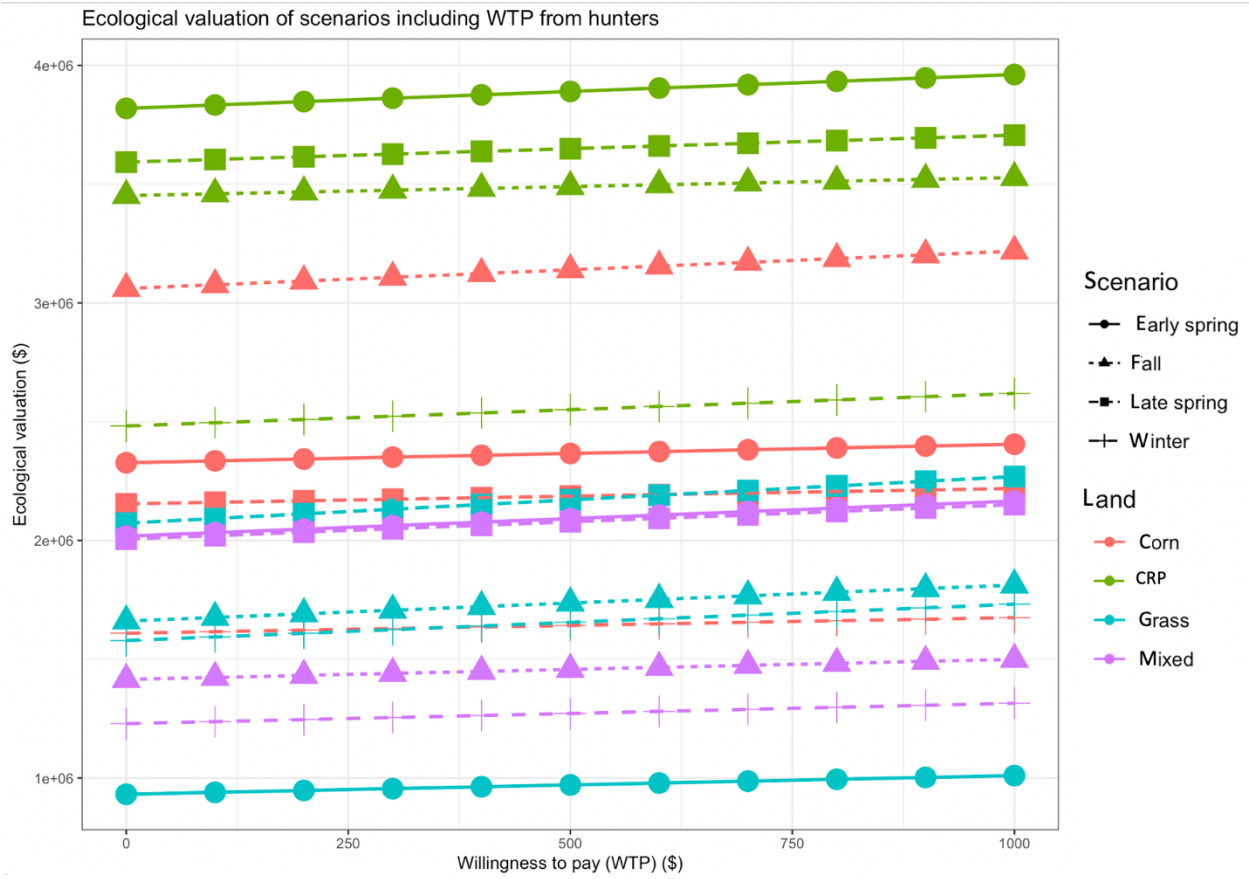

Figure 13. The total ecological valuation of each scenario when including variable hunter willingness to pay (WTP). Color denotes landscape (corn, CRP, grass, mixed) and point shape + linetype denote harvest scenario (fall, winter, early spring, late spring).

4. Discussion

We simulated both temporal and spatial harvest scenarios and found that both influenced total value garnered from the system. Comparing scenarios with harvest simulated at different times, we found that fall harvesting provided the most value. Our results suggest that harvesting in winter will result in lower biomass yield, and that this reduction in yield is not landscape dependent. This agrees with Gamble et al., (2015) who found that biomass yield was lowest when harvested in winter across seven sites in Minnesota. Biomass yield is lower when harvested in winter because of the degradation in plant material. Additionally, other studies have found that biomass yield is less in winter (Adler et al. 2006, Ashworth et al. 2017). We also found that harvesting in spring will result in fewer pheasants, because harvesting results in higher mortality during the nesting period. This has also been observed in the field (Best et al. 1995; Tesky 1995). We expected an inverse relationship between biomass yield and pheasant population sizes among different biomass harvest times. We did not see such a relationship. Instead, we found that harvesting biomass in the fall resulted in the highest values of both pheasant population and biomass generation.

We found ecological value to be landscape dependent. Our scenarios totaled between ~$931,000 (minimum) and $3.8 million (maximum) over all landscapes. CRP landscape- and corn landscape-scenarios were among the most lucrative and far surpassed values from grass landscape- and mixed landscape-scenarios, even without accounting for the direct payments to farmers for enrolling land in CRP.

Only one scenario (Fall, corn) had total value coming from roughly both sources equally. Otherwise, nine scenarios had much of their value come from pheasants and the other six scenarios depended on harvest yields for the majority of their value. All scenarios in the grass and mixed landscape and one CRP (winter) received most of their value from pheasants. Except for the two previously discussed exceptions, harvest yields provided the majority of the value of all corn and CRP scenarios. This makes sense because the corn landscape would have the most value gained through corn harvest. And, both corn and CRP landscapes contain the most land available for harvest. However, it is important to note that biomass markets do not currently exist. As a result, farmers cannot realize profits from feedstocks yet. Biomass markets are predicted to exist in the future (BETO 2016, Efroymson et al. 2017).

The most important conclusion we can draw from this study is that it is possible to preserve pheasant populations without sacrificing profits from crops. On average, harvesting in late spring generated the most value ($2.45 million) but harvesting in fall was a close second in terms of profitability ($2.39 million). Value from biomass was generally higher when harvest occurred in the fall than in late spring. Conversely, value from pheasants was typically higher when harvest occurred in the late spring than in the fall. Despite this, both scenarios generated comparable average valuations. Pheasant populations tend to be higher when biomass is harvested in the fall when compared with late spring (Figure 9, 12). Lastly, hunters WTP can drastically increase pheasant value. Taken together, it seems that preserving pheasant populations and still realizing crop profit are not incompatible.

As with any study, there were limitations inherent in the model. One limitation of our study is the lack of sensitivity analysis, which would explore the variability of parameters in the model. Given computational constraints, such an analysis was not run but provides fruitful ideas for future work. Though, this system could be formalized as an optimal control problem. Then, parameters would be determined from scenario simulation in the ABM and we could determine optimal harvest strategies given different objectives. Another limitation of this study is that the vegetation processes were deterministic when they are actually stochastic. While this allowed us to explicitly quantify trade-offs by normalizing crop yields, it would be interesting to add stochasticity to these processes in the future.

In this study, we utilized a novel agent-based model that simulated the spatiotemporal dynamics and interactions of four classes of agents. This complex ABM provided insights into best practices of harvesting and hunting in bioenergy landscapes. This model could be informative when designing biomass harvesting- and pheasant hunting- strategies.

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Supplemental

Full model code can be found at https://github.com/jaaykaay/PheasantABM

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