Spatiotemporal management under heterogeneous damage and uncertain parameters. An agent-based approach.

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Selected Paper prepared for presentation at the 2016 Agricultural & Applied Economics Association Annual Meeting, Boston, Massachusetts, July 31-August 2

Animal species can have intrinsic or commercial value while at the same time imposing costs, leading to disagreements over the desirability of the species and how it should be managed. The desirability of the species depends upon the evaluator with disagreement within disciplines such as agriculture or wildlife biology. One common argument against a species revolves around its status as native or non-native, with non-native as a negative characteristic. Defining native and non-native is highly subjective, with a standard North American delineation as Christopher Columbus's arrival in 1492 (Nelson 2010). In the 19th century, native species such as the American buffalo *(Bison bison)* were targets of eradication campaigns and even today white-tailed deer *(Odocoileus virginianus)* and Canadian geese *(Branta Canadensis)* populations are managed to limit the damage they inflict on agriculture. It is also acknowledged that these example species have intrinsic value in the ecosystem and value as a recreationally hunted species in the case of white-tailed deer and Canadian geese. Non-native species can be viewed beneficially, as most agricultural species are introduced; for recreational use; and even as a replacement for extirpated native species (Ameden et al. 2009; Hainds 2011; Schlaepfer, Sax, and Olden 2011; Zivin, Hueth, and Zilberman 2000). In the US, one species under debate is feral swine *(Sus scrofa)*. Federal removal and control efforts are underway while at the same time some private landowners encourage their growth on their property (Bannerman and Cole 2014; Bevins et al. 2014).

Feral swine cause ecosystem damage, physical losses to agriculture, and serve as a vector for diseases (Shwiff et al., Forthcoming). However, feral swine are a valuable recreational species. With benefits and costs often accruing to different people, conflict over management is inevitable. As in most externality problems, property lines do not inhibit damage. Unique to most externality problems is the way the damage causing agent can multiply and spread unaided once introduced regardless of property lines and most fencing efforts. Stakeholders include: landowners focused on agriculture and/or recreation, private conservationists, and government entities. Agriculturalists may be sensitive to crop damage and unwilling to sell hunts on their property to offset the damage. Recreational users may enjoy the opportunity to hunt feral swine or may be sensitive to habitat damage and predation on other game species. Private individuals may also own land with the expressed purpose of native habitat conservation. This division between agriculturalist, recreationalists, and conservationists is likely more of a continuum than a set of categories. Land users are often a mix of the three. Land users can also exhibit inconsistent preferences or a lack of information, implying a need to relax rationality assumptions. Finally, government entities are responsible for many goals including preservation of native species, maintenance of protective structures such as levees, and preventing outbreaks of dangerous diseases. These varying objectives can result in inconsistent policy outcomes (Karp et al. 2015).

Management decisions by one stakeholder will affect the outcomes of all stakeholders. Feral swine are responsive to human action moving across space through time. The variety of opinions, varying capital stocks, and the interaction between landowners, government agencies, and the swine themselves make an optimal policy solution; here defined as the policy solution with the highest total welfare gain; hard to determine. Traditional welfare approaches commit the fallacy of composition in the name of integrability, the property that allows consumers and producers to be added together and inferences about the individual to be made from what is known of the whole. To address these shortcomings, an agent-based modeling approach is used to determine the conditions under which an optimal solution can be found, what is the optimal solution, as well as how varying stakeholder opinions and rationality can change the optimal solution.

This paper will demonstrate the importance of the interaction between individuals across time and space over management decisions in a way that has not previously been published. Management paths are established for heterogeneous groups of agriculturalists, recreational land users, private conservationists, and a governmental entity with varying motivations. The setting for the simulations is a hypothetical rural environment with the potential for feral swine and crops, livestock, and habitat damage. Results from these simulations are compared to situations with individuals of heterogeneous preferences. The resulting model provides value as a decision tool for policy makers looking to address the presence and spread of feral swine.

1 Literature Review

Previous studies have evaluated the costs and/or benefits related to policy interventions (Higginbotham et al. 2008). For this analysis, costs associated with feral swine are related to three categories of destruction: damage, disease transmission, and depredation of livestock (Shwiff et al., Forthcoming). The absence of costs related to the presence of feral swine can also be thought of as the benefits of removal. The benefits of presence are primarily hunting related. Hunting revenue leads to competing objectives in management.

Crop and environmental damages from feral swine have been estimated at $800 million per year (Pimentel, Zuniga, and Morrison 2005). Local estimates in Georgia and Texas also estimated substantial amounts of damage to agriculture and property (Higginbotham et al. 2008; Mengak 2012). Damage to automobiles from crashes and to property from rooting have also been reported (Mayer and Johns 2011). Feral swine are known carriers of diseases that are dangerous to humans, livestock, and wildlife (Bengsen et al. 2014; Miller, Farnsworth, and Malmberg 2013). The threats to human health include influenza (Attavanich, McCarl, and Bessler 2011; Hall et al. 2008) and contamination of the human food supply (Arnade, Calvin, and Kuchler 2009; Kreith 2007). Feral swine could also spread diseases with severe trade consequences such as foot-and-mouth (FMD) to domestic livestock (Cozzens 2010; Cozzens, Gebhardt, and Shwiff 2010; Pineda–Krch et al. 2010; Ward, Laffan, and Highfield 2007, 2009). Their capacity to act as a vector of disease is potentially the greatest danger to life and property imposed by feral swine.

Of particular importance to agriculture is the fact that feral swine are known to prey on livestock. Primarily, feral swine prey on sheep *(Ovis aries)* and goats *(Capra hircus)*, but have been known to feed on larger animals such as cows *(Bos taurus)* and other exotic game species leading to substantial economic loss (Christie et al. 2014; Frederick 1998; Seward et al. 2004). Feral swine density was found to be a significant predictor of ewes losing lambs (Choquenot, Lukins, and Curran 1997). Feral swine are also known to feed on endangered species such as different species of amphibians

(Bevins et al. 2014; Seward et al. 2004). Attacks on humans are detailed in court cases and peer reviewed literature. Love (2013) describes the case of an inmate on a work crew who was attacked by a feral swine. Mayer (2013) found that up to fifteen percent of reported attacks on humans resulting in mauling are fatal, primarily due to blood loss, often from lacerations to the femoral artery. Most attacks are primarily defensive in nature, but they have been known to enter occupied buildings and attack as well as one documented case of a swine who repeatedly killed and ate humans (Mayer 2013).

Humans facilitate the spread of feral swine due to their popularity as a game species (Bevins et al. 2014; Kreith 2007). In many areas feral swine are regarded as native and control efforts by non-locals are met with resistance (Warner and Kinslow 2013; Weeks and Packard 2009). Some advocate that one damage mitigation technique is to capitalize on the presence of feral swine by offering commercial hunts (Adams et al. 2005). Embracing citizen hunting and commercial hunting results in revenue for states (Sweitzer and McCann 2007), surrounding economies (Dodd et al. 2013), and landowners (Tolleson et al. 1995; Zivin, Hueth, and Zilberman 2000). However, the damage introduced earlier has led some states to restrict citizen hunting in their efforts of working toward eradication (Hoekstra, Cavanagh, and Borrello; Lawrence 2013). In other states, legal structures exist that could prevent the prohibition of commercial hunting without compensating those who are losing a previously held property right due to the new regulation (Echeverria and Hansen-Young 2008; Grout, Plantinga, and Jaeger 2014).

The question for policymakers is what, if any, action should be undertaken with respect to feral swine. As in most cases of developing a social welfare function, some weighting scheme must be developed. Regardless of what social welfare function is chosen, these tradeoffs have not been explored in a feral swine context. The literature does have examples of weighing the costs and benefits of feral swine from an individual profit-maximizing operator's perspective using a bioeconomic model (Zivin, Hueth, and Zilberman 2000). Melstrom (2014) compared eradication to perpetual control with a goal of preserving a competing species on an island using optimal control theory. Generalizing from feral swine, modeling the tradeoffs between commercially valuable species and other goals and activities has been modeled. For example, using a stochastic dynamic programming model Grechi et al. (2014) weighed the commercial value of buffel grass against biodiversity objectives in Australia. Damage compensation schemes have been modeled with moral hazard in mind with a principal-agent model (Rollins and Briggs III 1996). Jones et al. (2012) used an economic harvest model combined with a spatial population model to determine if a sustainable opossum harvest can also meet objectives relating to biodiversity and bovine TB mitigation goals. Nalle et al. (2004) developed a spatially explicit method for balancing timber and wildlife production using a three-dimensional production possibilities frontier. These different modeling techniques were either unable to model multiple autonomous, interactive agents in time and space or did so by coupling different models together. Agent-based modeling promises to be able to model a rich diversity in objectives across time and space (Heckbert, Baynes, and Reeson 2010).

Agent-based modeling excels at spatially explicit simulation of autonomous interactive agents. Ross and Westgren (2009) used a rules-based agent-based model (ABM) to show the importance of entrepreneur characteristics by modeling the rents creation process in agrifood innovations. Ameden et al. (2009) developed an ABM to model interactions between importers and border enforcement agents with a spatially explicit damage function to show how different enforcement regimes affect invasive species risk. Happe et al. (2009) found the structure of direct payments to farmers is important to the outcomes of smaller farms by using an available ABM named AgriPoliS that appears to be no longer maintained. Freeman, Nolan, and Schoney (2009) examined the effect of management styles and risk preferences, factor endowments, and government payments on farm size, size structure, and success and found factor endowments and government payments to be significant determinants.

Particularly interesting among agent-based models are models that integrate other tools such as linear programming or constrained optimization to guide their agents in a way that is consistent with economic theory. Agent-based models (ABM) have been used to analyze land cover changes (Evans and Kelley 2004). Evans and Kelley (2004) modeled heterogeneous agents choosing land cover in a single township located in south-central Indiana and varied the spatial resolutions to find that smaller resolutions calibrate better than larger resolutions. Agents were constrained expected utility maximizing, and parameters were chosen to calibrate the model to observed land use (Evans and Kelley 2004). An ABM was used in combination with linear programming methods to analyze technology diffusion in a spatially explicit manner set in a developing country context to find the potential outcome of a new economic cooperation agreement (Berger 2001). Schreinemachers et al. (2009) advanced the technique of using linear programming as the basis of agent decision-making and allowing agents to base future expectations on past observances and then revise those expectations periodically.

Berger (2001) demonstrated that ABMs can help the analyst work with extremely limited data availability. Berger and Troost (2014) took this idea further by simulating previously unseen and uncertain climate change effects and demonstrating the capability of ABMs to evaluate policy outcomes under this uncertainty. Troost and Berger (2015) continued work on agricultural responses to climate change by modeling farmer decision making through a mixed integer programming routine within an agent based model. Troost and Berger (2015) advocated the reduction of uncertain parameter values through model calibration based on known outcomes.

This literature shows that we can inform policy in situations where we do not have adequate statistical information to predict the outcome. We can use what we know about individual utility maximization and feral swine to predict outcomes when people do not agree. These applications of agent-based modeling demonstrate its capabilities with heterogeneous agents and spatially explicit modeling. Feral swine interact with landowners and government agents moving across space. We can adjust neoclassical assumptions about rationality and knowledge and use tools such as linear programming that are well known in other economic applications.

2 Theoretical Framework

To examine the effects of agent heterogeneity and interaction on feral swine management an agent-based model has been built. In this section the model is presented in general terms. The primary driver in choosing the agent-based model is its ability to model interaction of agents in time and space. Also important is the fact that individuals are interacting simply by pursuing their own objectives.

The individuals within an agent-based modeling framework are known as agents. Agents pursue their goals and interact within their environment. To answer our question, three types of agents are needed. The most intricately described agents are land users. Land users interact with their environment and the other two types of agents, feral swine and government.

Land users are expected utility maximizers. Based on an initial allocation of resources and preferences agents choose the course of action that best fits their situation. Each year agents update their resources and solve their optimization problem again. Land users are given preference parameters, $\alpha_{\jmath}$, for each activity, $\jmath$. The expected utility is a function of the levels of activity, $a_{\jmath}$.

$$E(u_{\imath}(a_1 \ldots a_J)) \tag{1}$$

The modeled land users exhibit commonly held assumptions of consumer behavior. These include that the consumption set, A, is the set of all conceivable commodity bundles defined according to all attributes such as quality, location, date. There are a finite number of commodities and consumption of those commodities must be non-negative, $A \subseteqq \mathbb{R}^n_+$. The consumption set includes the origin ($0 \in A$), the consumption decision is non-trivial ($A \neq \emptyset$). Consumer behavior is modeled to be consistent with two core preference axioms: completeness ($\forall\ a$ and $a' \in A$ either $a \succsim a'$ or $a' \succsim a$) and transitivity ($\forall\ a,\ a'$, and $a''\ \in A$ if $a \succsim a'$ and $a' \succsim a''$ then $a \succsim a''$).

Land users are also budget constrained on three dimensions. Each land user is allocated an initial wealth of land and money. They are able to influence the amount of money they have in subsequent periods by deciding how to allocate their land and time. Time is equally allocated. Formally, the consumers problem is:

$$\max_{a \in A} E(u_{\imath}(a_1 \ldots a_n))\ s.t.\ w(a_1 \ldots a_n) = 0. \tag{2}$$

This model attempts to hold land users to a minimal level of rationality as humans have complex motivations and full rationality may be too strong a set of assumptions (Coase 1960; North 1990; Simon 1955). To model complex rural behavior we first have to acknowledge that people own and use rural land for a variety of reasons. Land users can be placed on a spectrum between productivist and non-productivist where the former are primarily concerned about agricultural production and the latter are not concerned about production (Barbieri and Valdivia 2009). These groups also differ about their receptiveness to non-traditional land use such as agro-tourism or offering commercial hunts (Barbieri and Valdivia 2009). The reason people are on this spectrum is because individuals all have different upbringing, values, see themselves in their community differently, and communities differ in their norms (Shucksmith and Herrmann 2002). Shucksmith and Herrmann (2002) conceptualized this idea into a concept known as *"disposition–to–act."* The expression of this idea is that all farmers have an idea of what a "good farmer" is. This idea of what a "good farmer" is and how they view themselves in relationship to that concept will determine how receptive they are to non–traditional uses of their land (Barbieri and Valdivia 2009). Decisions involving wildlife has added complexity due to the questions of morality surrounding land-use that has been codified in the wildlife value orientation scale (Harper, Forthcoming). Options not compatible with either the landowner's disposition-to-act or wildlife value orientation will simply not be considered regardless of financial incentives (Harper, Forthcoming; Shucksmith and Herrmann 2002). Reconciling these statements with the mathematical expressions above, land users have preferences regarding their consumption of a_J where J may be the act of farming in addition to the preference for wealth. Land users may have a high preference for hunting ($\alpha_{hunting} \rightarrow 1$), but find hunting feral swine with dogs abhorrent. Possible courses of action that are not consistent with their values simply are not in A.

Government is a social welfare maximizer. In the following section, how the government counts social welfare and how it impacts social welfare will be discussed. In the theoretical context here,

$$\Omega(u_1 \ldots u_I). \tag{3}$$

The government affects the utility of its stakeholders by choosing to enact policies, ϕ. The policies in this case are regarding feral swine. The set of government choices, Z, includes encouraging feral swine, ignoring feral swine, or removing feral swine from any given parcel. This affects the number of feral swine on the map and thus the utility of the land users on the map. Government is also budget constrained, but this is endogenously determined. The government's problem is:

$$\max_{\phi \in Z} \Omega(u_1(a_1 \ldots a_J) \ldots u_n(a_1 \ldots a_J)) \; s.t. \; h(\phi_1 \ldots \phi_n) = 0. \tag{4}$$

For the sake of tractability, feral swine are modeled relatively simply. They are modeled as driven by a movement function. It is assumed that they will have adequate food on any plot of ground, however some food sources are more attractive than others. They seek to avoid removal and crowded locations.

$$movement(food,\ removal\ pressure,\ population\ pressure). \tag{5}$$

The model consists of agents placed on a landscape. The landscape is set to be a Public Land Survey System (PLSS) township. This is 36 sections, 36 square miles, or 17,280 acres.

Time is defined in year intervals. Agents are assigned an initial endowment of resources. At the beginning of the first period, the agents act on their objective function. At the end of the year the agents realize the consequences of their actions. Each subsequent period, the agents solve their objective functions based on updated parameters and resource levels.

Removal of feral swine is progressively more expensive as the population decreases (Saunders and Bryant 1988). This is because feral swine learn and respond to attempts at removal. This means that removal of feral swine should be modeled as a stochastic process where the probability of removing a given animal on a given parcel is a function of effort of the land user or government and the density of feral swine on that parcel. The learning process implies that the probability of removal is also a function of effort expended in the previous period.

$$Pr(Removal) = pd(effort_{lu},\ effort_{govt},\ density_{fs},\ \sum effort_{t-1}) \tag{6}$$

Feral swine reproduce very quickly. It is estimated that one must remove 66 percent of a population to keep the number steady (Timmons et al. 2012). Logistic growth functions are commonly used to describe species growth. This however, is a population function. Each animal in the model has its own probability of having offspring. The size of surviving litter is a function of the quality of the parcel the swine is present on and the intensity of control efforts.

$$litter(quality,\ removal\ pressure) \tag{7}$$

Damage by feral swine has been shown to be a function of density (Hone 1995).

$$damage(density) \tag{8}$$

To conduct experiments, key output variables will be recorded. These include utility of each individual, number of feral swine removed and by who, and a census. Optimal management implies that the highest utility of those affected is reached at the lowest cost. Given the functional forms just described, one should expect a reasonably accurate simulation. To answer our question, the model will be simulated thousands of times, each time recording key output variables. Each simulation is indexed on ℓ. Several experiments will be conducted.

The simplest experiment would be to limit the landscape to two land users and impose actions regarding feral swine on one of the players to show the impact on the other player. Another experiment would consider the differences in government action due to different social welfare functions.

The question at hand is how to measure optimal management and agent heterogeneity. Land owner heterogeneity is a function of the agents' preference parameters and as a model the analyst has access to those parameters. The analyst also has access to private and public spending on feral swine control. Utility of each agent can also be recorded. One tool comes to mind to find a statistically powerful link between covariates or explanatory variables and a dependent variable over time, where the periods are not independent—survival analysis.

With survival analysis models one can test for contributing factors to a given individual's survival. In this case, explaining the length of time before a given feral swine dies would be explained by factors of interest. From Greene (2012, p. 869), a survival function can be stated:

$$S(t) = E_v[S(t|v)] = \int_v S(t|v)f(v)\mathrm{d}v \tag{9}$$

for estimation through maximum likelihood. Alternatively, nonparametric and semiparametric approaches can be used (Han and Hausman 1990).

3 Theoretical Framework Applied

In the previous section, functions were defined generally. In this section, the functional form of the different functions will be specified. Mathematical representations of the model are supported with relevant portions of code.

Land ownership is randomly assigned. The size of parcels and number of owners is a function of the algorithm used. Essentially, Wilensky (2013) was modified to work within the framework of our model.

Listing 1: Plot generation for land ownership.

```
    to setup-setupclusters
  ask patches
  [ ;; use dark colors so the labels are visible
    set pcolor 3 + 10 * random 14
    ;; initially, we're in no cluster
    set cluster nobody ]
  ;; by spreading colors from patch to patch, connected areas
  ;; that are all the same color will emerge
  repeat cluster-var
  [ ask patches
    [ set pcolor [pcolor] of one-of neighbors4 ] ]
  find-clusters
end

to find-clusters
  loop [
    ;; pick a random patch that isn't in a cluster yet
    let seed one-of patches with [cluster = nobody]
    ;; if we can't find one, then we're done!
    if seed = nobody
    [ show-clusters
      stop ]
    ;; otherwise, make the patch the "leader" of a new cluster
    ;; by assigning itself to its own cluster, then call
    ;; grow-cluster to find the rest of the cluster
    ask seed
    [ set cluster self
      grow-cluster ]
  ]
end

to grow-cluster ;; patch procedure
  ask neighbors4 with [(cluster = nobody) and
    (pcolor = [pcolor] of myself)]
  [ set cluster [cluster] of myself
    grow-cluster ]
end

;; once all the clusters have been found, this is called
;; to put numeric labels on them so the user can see
```

```
;; that the clusters were identified correctly

to show-clusters
  let counter 0
  loop
  [ ;; pick a random patch we haven't labeled yet
    let p one-of patches with [plabel = ""]
    if p = nobody
      [ stop ]
    ;; give all patches in the chosen patch's cluster
    ;; the same label
    ask p
    [ ask patches with [cluster = [cluster] of myself]
      [ set plabel counter ]
      ]
    set counter counter + 1 ]
end
```

Patches, the smallest unit of physical space in this model, are given certain characteristics. Patches are given quality, desirability, costs of production, and revenue associated with land use choices.

Listing 2: Patch endowment.

```
to setup-patches
  ask patches [
    set quality random-float 100 ;;set quality for yield, cost
    set fertility random-float 1 ;;set fertility to 1, so full
        fertility
    set food random-float 1 ;;set food attractiveness of parcel
        to full attractiveness
    set owner -1 ;;set land as unclaimed
    set fallow 0 ;;sets counter for land fallow at 0
    set pigcount 0 ;;sets the pig count on a parcel at 0
    set prohuntpig 0 ;;sets the initial commercial hunting effort
        at 0
    set freehuntpig 0;;sets the initial free hunting effort at 0
    set govhuntpig 0 ;;sets the initial government hunting effort
        at 0
    set psi 0 ;;sets the initial total effective hunting effort
        at 0
    set psi_t-1 0 ;;sets initial previous period hunting effort
        at 0
    set max_pigs max_pigs_sq_mi / 32 ;;adjusts pigs per sq mi to
        20 acre parcels
    set a_corn 0 ;; binary corn or not
    set a_soy 0 ;; binary soybeans or not
```

```
    set a_huntP4free 0 ;;
    set a_huntO4free 0
    set a_huntP4M 0
    set a_huntO4M 0
    set a_CRP 0
    set effect_comm random-float 1
    set effect_free random-float 1
    set effect_govt random-float 1
    set memory random-float 1
    set breedscore random-float 1
    set parcel_NI 0
      ; revenue per parcel
    set r_corn (Egm_corn + m_corn) * quality
    set r_soy (Egm_soy + m_soy) * quality
    set r_huntP4free (Egm_huntP4free + m_huntP4free) * quality
    set r_huntO4free (Egm_huntO4free + m_huntO4free) * quality
    set r_huntP4M (Egm_huntP4M + m_huntP4M) * quality
    set r_huntO4M (Egm_huntO4M + m_huntO4M) * quality
    set r_offfarm (Egm_offfarm + m_offfarm) * quality
    set r_CRP (Egm_CRP + m_CRP) * quality
  ; cost per parcel
    set c_corn (m_corn) * 1 / quality
    set c_soy (m_soy) * 1 / quality
    set c_huntP4free (m_huntP4free) * 1 / quality
    set c_huntO4free (m_huntO4free) * 1 / quality
    set c_huntP4M (m_huntP4M) * 1 / quality
    set c_huntO4M (m_huntO4M) * 1 / quality
    set c_offfarm (m_offfarm) * 1 / quality
    set c_CRP (m_CRP) * 1 / quality

    ]
end
```

Land users are placed on the landscape randomly. Each of the clusters defined above are asked to create a household on one patch. Each of those households are then endowed with wealth and preference parameters. Wealth and preference parameters are randomly assigned using a uniform distribution between zero and a user specified value.

Listing 3: Set Up Land Users.

```
to setup-sprouts
  ask patches [
  set cluster-list [cluster] of patches]
  set cluster-list remove-duplicates cluster-list
  foreach cluster-list [ask one-of patches with [cluster = self]
      [sprout-households 1 set plabel ""
```

```
    ask households-here [set clusterhh cluster]
     ]
   ;
  ]
end
to setup-households
   let hh 1
   ask households [
     set wealth random-float 100000
     set hh_num hh
     let c hh_num
     let d clusterhh
     set label hh_num
     set alpha_corn random-float (alpha_corn_i / 100)
     set alpha_soy random-float (alpha_soy_i / 100)
     set alpha_huntP4free random-float (alpha_huntP4free_i / 100)
     set alpha_huntO4free random-float (alpha_huntO4free_i / 100)
     set alpha_huntP4M random-float (alpha_huntP4M_i / 100)
     set alpha_huntO4M random-float (alpha_huntO4M_i / 100)
     set alpha_crp random-float (alpha_crp_i / 100)
     set alpha_offfarm random-float (alpha_offfarm_i / 100)
   ask patch-here [set pcolor red set farmstead 1 set fertility
       0] ; build a farmstead but you can't farm here
   ;ask other patches in-radius claim_radius with [owner = -1]
   ask other patches with [cluster = d and owner = -1]
     [set owner c set fallow 0
      ; set pcolor 65
     ] ; household takes ownership of unowned patches in area
         around farmstead
     set hh hh + 1
   ]
end
```

A user specified number of feral swine are created and placed randomly.

Listing 4: Set Up Feral Swine.

```
to setup-pigs
  create-pigs init_pigs
  [ set pig_num who
    set size 1
    set color blue
    set litter 0
    set age 0
    setxy random-xcor random-ycor]
end
```

The land user's problem is to maximize their utility subject to their constraints. The application will be calculated as a mixed integer programming model (MIP) and will be specified as such here. The user's objective is to maximize utility (u_i) by choosing activity (a_J). The user's decision is how to allocate his land, labor, and capital to best maximize utility. The user maximizes over a five year time horizon and over each parcel of land they have control over. The user's constraints are land (P), time (T), and capital (M). Each activity (a_J) is associated with a cost in terms of land (p_J) and time (t_J). Some activities generate income, while others simply cost money (m_J). The J activities available are: corn, soybeans, work off farm, hunt feral swine for free, charge for feral swine hunts, hunt other species for free, charge to hunt other species, and the conservation reserve program (CRP). The system of equations is: Objective:

$$
\begin{gathered}
max_{a_{J,t} \in A} u_i = \\
(\alpha_{corn} * \ln a_{corn}^{p=1,t=1} + \alpha_{soy} * \ln a_{soy}^{p=1,t=1} + \alpha_{huntFS4free} * \ln a_{huntFS4free}^{p=1,t=1} + \alpha_{huntO4free} * \ln a_{huntO4free}^{p=1,t=1} \\
+ \alpha_{huntFS4\$} * \ln a_{huntFS4\$}^{p=1,t=1} + \alpha_{huntO4\$} * \ln a_{huntO4\$}^{p=1,t=1} + \alpha_{OFW} * \ln a_{OFW}^{p=1,t=1} + \alpha_{CRP} * \ln a_{CRP}^{p=1,t=1})^{p=1,t=1} \\
+ \ldots + \\
(\alpha_{corn} * \ln a_{corn}^{p=P,t=1} + \alpha_{soy} * \ln a_{soy}^{p=P,t=1} + \alpha_{huntFS4free} * \ln a_{huntFS4free}^{p=P,t=1} + \alpha_{huntO4free} * \ln a_{huntO4free}^{p=P,t=1} \\
+ \alpha_{huntFS4\$} * \ln a_{huntFS4\$}^{p=P,t=1} + \alpha_{huntO4\$} * \ln a_{huntO4\$}^{p=P,t=1} + \alpha_{OFW} * \ln a_{OFW}^{p=P,t=1} + \alpha_{CRP} * \ln a_{CRP}^{p=P,t=1})^{p=P,t=1} \\
+ \ldots + \\
(\alpha_{corn} * \ln a_{corn}^{p=1,t=T} + \alpha_{soy} * \ln a_{soy}^{p=1,t=T} + \alpha_{huntFS4free} * \ln a_{huntFS4free}^{p=1,t=T} + \alpha_{huntO4free} * \ln a_{huntO4free}^{p=1,t=T} \\
+ \alpha_{huntFS4\$} * \ln a_{huntFS4\$}^{p=1,t=T} + \alpha_{huntO4\$} * \ln a_{huntO4\$}^{p=1,t=T} + \alpha_{OFW} * \ln a_{OFW}^{p=1,t=T} + \alpha_{CRP} * \ln a_{CRP}^{p=1,t=T})^{p=1,t=T} \\
+ \ldots + \\
(\alpha_{corn} * \ln a_{corn}^{p=P,t=T} + \alpha_{soy} * \ln a_{soy}^{p=P,t=T} + \alpha_{huntFS4free} * \ln a_{huntFS4free}^{p=P,t=T} + \alpha_{huntO4free} * \ln a_{huntO4free}^{p=P,t=T} \\
+ \alpha_{huntFS4\$} * \ln a_{huntFS4\$}^{p=P,t=T} + \alpha_{huntO4\$} * \ln a_{huntO4\$}^{p=P,t=T} + \alpha_{OFW} * \ln a_{OFW}^{p=P,t=T} + \alpha_{CRP} * \ln a_{CRP}^{p=P,t=T})^{p=P,t=T} \\
+ \alpha_{money} * \ln M_{t=1} + \alpha_{money} * \ln (M_{t=2} * (1+r)^{-2}) + \ldots + \alpha_{money} * \ln (M_{t=5} * (1+r)^{-5})
\end{gathered}
\tag{10}
$$

Maximization of this utility function is subject to the following constraints. A given parcel can only be used for one crop and each parcel must be used completely by that use.

$$a_{k=\{1,\ldots,K\}}^{p=\{1,\ldots,P\},t=\{1,\ldots,T\}} = \{0,1\} \tag{11}$$

$$1 \geq a_{corn}^{p=1,t=1} + a_{soy}^{p=1,t=1} + a_{CRP}^{p=1,t=1} \tag{12}$$

...

$$1 \geq a_{corn}^{p=P,t=1} + a_{soy}^{p=P,t=1} + a_{CRP}^{N=1,t=1} \tag{13}$$

...

$$1 \geq a_{corn}^{p=1,t=5} + a_{soy}^{p=1,t=5} + a_{CRP}^{p=1,t=5} \tag{14}$$

...

$$1 \geq a_{corn}^{p=P,t=5} + a_{soy}^{p=P,t=5} + a_{CRP}^{N=1,t=5} \tag{15}$$

A given parcel can either only be used for commercial hunting or free hunting and hunting for feral swine and other species is allowed, however this arrangement will harm the hunting of other species by Ψ.

$$1 \geq a_{huntFS4\$}^{p=1,t=1} + \Psi a_{huntO4\$}^{p=1,t=1} \tag{16}$$

...

$$1 \geq a_{huntFS4\$}^{p=P,t=1} + \Psi a_{huntO4\$}^{p=P,t=1} \tag{17}$$

...

$$1 \geq a_{huntFS4\$}^{p=1,t=5} + \Psi a_{huntO4\$}^{p=1,t=5} \tag{18}$$

...

$$1 \geq a_{huntFS4\$}^{p=P,t=5} + \Psi a_{huntO4\$}^{p=P,t=5} \tag{19}$$

$$1 \geq a_{huntFS4free}^{p=1,t=1} + \Psi a_{huntO4free}^{p=1,t=1} \tag{20}$$

...

$$1 \geq a_{huntFS4free}^{p=P,t=1} + \Psi a_{huntO4free}^{p=P,t=1} \tag{21}$$

...

$$1 \geq a_{huntFS4free}^{p=1,t=5} + \Psi a_{huntO4free}^{p=1,t=5} \tag{22}$$

...

$$1 \geq a_{huntFS4free}^{p=P,t=5} + \Psi a_{huntO4free}^{p=P,t=5} \tag{23}$$

The users are able to build or lose wealth and they are not able to spend more than is available in a given period. An expected gross margin figure is used to budget over the optimization period.

$$m_J^{p,t} = \frac{\sum_{t=t-3}^{t=t-2}(R_{J,p} * D(N_{p,t} * a_{J,t})}{3} - \frac{\sum_{t-3}^{t-1}(W_{J,p} * a_{J,t})}{3} \tag{24}$$

$$M_{t=1} = \sum_{J=1}^{J} \sum_{p=1}^{P} (m_J^{p,t} a_J^{p,t}) + initial\ endowment \tag{25}$$

$$M_{t=2} = \left(\sum_{J=1}^{J} \sum_{p=1}^{P} (m_J^{p,t} a_J^{p,t}) + M_{t=1} \right) \tag{26}$$

$$M_{t=3} = \left(\sum_{J=1}^{J} \sum_{p=1}^{P} (m_J^{p,t} a_J^{p,t}) + M_{t=2} \right) \tag{27}$$

$$M_{t=4} = \left(\sum_{J=1}^{J} \sum_{p=1}^{P} (m_J^{p,t} a_J^{p,t}) + M_{t=3} \right) \tag{28}$$

$$M_{t=5} = \left(\sum_{J=1}^{J} \sum_{p=1}^{P} (m_J^{p,t} a_J^{p,t}) + M_{t=4} \right) \tag{29}$$

The users only have 365 days each year to spend.

$$365 \geq \sum_{p=1}^{P}\sum_{J=1}^{J}(t_J a_J^{p,t=1}) \tag{30}$$

$$365 \geq \sum_{p=1}^{P}\sum_{J=1}^{J}(t_J a_J^{p,t=2}) \tag{31}$$

$$365 \geq \sum_{p=1}^{P}\sum_{J=1}^{J}(t_J a_J^{p,t=3}) \tag{32}$$

$$365 \geq \sum_{p=1}^{P}\sum_{J=1}^{J}(t_J a_J^{p,t=4}) \tag{33}$$

$$365 \geq \sum_{p=1}^{P}\sum_{J=1}^{J}(t_J a_J^{p,t=5}) \tag{34}$$

This optimization process is coded as below. Currently, the household is only optimizing over a single period. The land owner is also currently constrained to carrying out the same action on all of his patches. An extension that adds linear programming capability developed by MacKenzie (2016) was used for the decision making of land users.

Listing 5: Land User MIP Problem.

```
to go-households
 ask households[
   let f hh_num
   set parcels count patches with [owner = f] ;;count number of
       parcels owned by household
   go-optimize
  ]
end
to go-optimize ;; all land with the same owner is used for the
    same use.
   let time (list t_corn t_soy t_huntP4free t_huntO4free
       t_huntP4M t_huntO4M t_offfarm t_CRP 1 365)
   let cost (list m_corn m_soy m_huntP4free m_huntO4free
       m_huntP4M m_huntO4M m_offfarm m_CRP 1 wealth)
   ;only one land use per parcel;; all land goes into the same use
   let land1 (list 1 1 0 0 0 0 0 1 1 1)
   ;only one FS hunting per land
   let land2 (list 0 0 1 0 1 0 0 0 1 365)
   ;only one other hunting per land
   let land3 (list 0 0 0 1 0 1 0 0 1 365)
   ;FS hunting will hinder other hunting
```

```
let land4 (list 0 0 1 PsiPen 0 0 0 0 1 365)
let land5 (list 0 0 0 0 1 PsiPen 0 0 1 365)
let Egm (list Egm_corn Egm_soy Egm_huntP4free Egm_huntO4free
    Egm_huntP4M Egm_huntO4M Egm_offfarm Egm_CRP 2 min_income)
let numvar 8
let obj (list alpha_corn alpha_soy alpha_huntP4free
    alpha_huntO4free alpha_huntP4M alpha_huntO4M alpha_offfarm
    alpha_CRP)

let con (list
  time
  cost
  Egm
  land1
  land2
  land3
  land4
  land5
  )
let bins [2 2 1 1 1 1 1 2]

set results lpsolver:max numvar con obj bins
print results
ifelse item 1 results = 1 [ask patches with [owner = self]
    [set a_corn 1 set damage dam_corn * count pigs-here ]][ask
    patches with [owner = self][ set a_corn 0]]
ifelse item 2 results = 1 [ask patches with [owner = self]
    [set a_soy 1 set damage dam_soy * count pigs-here]][ask
    patches with [owner = self][ set a_soy 0]]
let aa1 item 3 results
ifelse item 3 results > 0 [ask patches with [owner = self]
    [set a_huntP4free aa1]][ask patches with [owner = self][
    set a_huntP4free 0]]
let aa2 item 4 results
ifelse item 4 results > 0 [ask patches with [owner = self]
    [set a_huntO4free aa2]][ask patches with [owner = self][
    set a_huntO4free 0]]
let aa3 item 5 results
ifelse item 5 results > 0 [ask patches with [owner = self]
    [set a_huntP4M aa3]][ask patches with [owner = self][ set
    a_huntP4M 0]]
let aa4 item 6 results
ifelse item 6 results > 0 [ask patches with [owner = self]
    [set a_huntO4M aa4]][ask patches with [owner = self][ set
    a_huntO4M 0]]
let aa5 item 8 results
```

```
   ifelse item 8 results = 1 [ask patches with [owner = self]
       [set a_CRP 1]][ask patches with [owner = self][ set a_CRP
       0]]
   let aa6 item 7 results
   ifelse item 7 results = 1 [ask households with [hh_num = self]
       [set a_offfarm aa6]][ask households with [hh_num = self][
       set a_offfarm 0]]
; a_money effect_comm effect_free effect_govt govt_act pigcensus
end
```

Each year the government pursues a course of action ($\phi = [-1, ..., 1]$) with regard to feral swine. The government can ignore, encourage, or remove feral swine. The government chooses its action by maximizing a social welfare function. The choice of policy will indirectly affect the utility of its stakeholders. Government is budget constrained in each period and has no incentive to conserve resources in any period. We will consider three social welfare functions, first is the Benthamite social welfare function with equal weighting on the outcome of all individuals (Just, Hueth, and Schmitz 2004):

$$\max_{\phi} \Omega(U_\iota, \phi) = \sum_{\iota} U_\iota \ s.t. \ B - b_\phi \phi = 0. \tag{35}$$

The Rawlsian social welfare function implies that the outcome of the worst off individual should be maximized because the decision is undertaken as if the decision maker does not know who they are after the decision is made such that (Just, Hueth, and Schmitz 2004):

$$\max_{\phi} \Omega(U_\iota, \phi) = \min\left(U_\iota, \iota = 1, \ldots, I\right) \ s.t. \ B - b_\phi \phi = 0. \tag{36}$$

The final option is for the government to weigh the utility of its stakeholders by their wealth ($M_{i,t}$):

$$\max_{\phi} \Omega(U_\iota, \phi) = \sum_{\iota} M_\iota U_\iota - \ \ s.t. \ B - b_\phi \phi. \tag{37}$$

The movement of feral swine is a function of food, removal pressure, and population pressure. For each feral swine, biological growth is given by:

$$offspring = (x \in uniform(0, 0.5 * \mu, 20)) * \xi * \psi \tag{38}$$

where litter size is a function of a draw from a distribution centered on mean yearly offspring (μ), quality of the parcel the pig is on that year ($\xi_p = [0, ..., 1]$), and removal pressure ($\psi_{p,t} = [0, ..., 1]$).

In the model, the function above is used to determine how fertile feral swine on a given patch are and this is used to determine the litter borne by each swine each period. Currently, the litter is deterministic with no random component.

Listing 6: Feral Swine Reproduction.

```
to go-breedscore ;;each parcel has a carrying capacity
  let localbreedscore 0
```

```
  ask patches [
    set breedscore quality * psi ;;quality * hunting pressure
  ]
  ask pigs [set localbreedscore breedscore
            set localbreedscore localbreedscore / 10.0
            set litter localbreedscore ;; set litter size for each
                pig based on their location
; type "LITTER: " print litter
           ] ; !!!! ADD RANDOM COMPONENT random-float 10. or the
               like
  end

to go-pighatch ; pigs birth a litter based on litter variable
  ask pigs [
; print " "
; type "Pigs: " print count pigs
; type "Litter: " print litter
    hatch litter set age 0
   ]
end
```

Feral swine have some food preferences and are sensitive to over-crowding and removal pressure. Each period the pig will look at the four directly adjacent parcels and evaluate food, density, and removal pressure. The cell with the highest score is where the pig will go:

$$score_p^t = min(1, \frac{food_{p,t}}{1} * \frac{k_p}{N_{p,t}} * \psi_{p,t}) \tag{39}$$

where the score is a maximum of one, and is a function of food quality ($food_{p,t}$ = [0, ..., 1]), inverse population density where k_p is the maximum number of swine per parcel and $N_{p,t}$ are the number present, and ψ as defined above.

Listing 7: Feral Swine Movement.

```
to go-score ;;pigs evaluate surroundings score the desirability
    of each parcel (patch) to feral swine
  ;ask patch 3 -4 [ set pcolor green ]
  ask patches [
    set score 0
    set pigcount count pigs-here
    set score ((food / 1)+(max_pigs / max (list 5.96e-08
        pigcount))+(psi)) ;; still trying to work out the proper
        functional form for this
  ]
    ; show score
end
```

```
to go-pigs ;;pigs look in 4 neighboring cells and go to the
    highest scoring cell ;;move if necessary
  ask pigs [
    uphill4 score
  ]
end
```

Effective removal effort in a given parcel is given by:

$$\psi_{p,t} = min(1, \varepsilon_p * a^{p,t}_{huntFS4\$} + \epsilon_p * a^{p,t}_{huntFS4free}) * (\eta * \phi) * (\Psi * \psi_{p,t-1})) \tag{40}$$

and the removal of an individual feral swine is given by:

$$Removed = \lfloor \rho * \psi_{p,t} \rceil. \tag{41}$$

Removal effort ($\psi_{p,t}$) is the minimum of one and the stated expression where $\varepsilon_p = [0, ..., 1]$ is the effectiveness of commercial hunting on parcel p, $\epsilon_p = [0, ..., 1]$ is the effectiveness of free hunting, $\eta = [0, ..., 1]$ is the effectiveness of government efforts, and $\Psi = [0, ..., 1]$ is the strength of feral swine memory of previous control attempts on that parcel. A partially dead feral swine is meaningless, thus the variable for an individuals removal is rounded to zero or one ($\lfloor \rho * \psi_{p,t} \rceil$). Removal of the individual is a function of a random variable, ($\rho = uniform(0, 1)$) which gives individual variability in removal and effort given by $\psi_{p,t}$. Also part of this script are several reporters for use in analysis.

Listing 8: Feral Swine Removal.

```
;;calculate psi, it is initially set to 0 in the setup script
to go-psiCalc
    ask patches [
      set psi effect_free * a_huntP4free + effect_comm *
          a_huntP4M + effect_govt * govt_act + memory * psi_t-1;;
          still trying to work out the proper functional form for
          this
      set psi_t-1 psi
    ; show psi
    ]
end

to go-removeFS ;;loop through patches, calculate probability of
    removal p>50\% for given pig dies.
  let rho random-float 1 ;; random part of removal
  let killedlistempty "true"
  ask patches [
    set pigcensus count pigs-here
    let cc3 (pigcensus - 2 * max_pigs)
    ask pigs-here [if psi * rho > 0.5 [
```

```
       hatch-killed 1 [ht]
       die
        ]] ;; targeted removal
   if cc3 > 0 [ask n-of cc3 pigs-here [
       hatch-dead 1 [ht]
       die
        ] ] ;; population max removal
  ]
  set killed-list [age] of killed
  set dead-list [age] of dead
  set dead-count count dead
  set dead-mean ifelse-value empty? dead-list ["na"] [mean
      dead-list]
  set killed-count count killed
  set killed-mean ifelse-value empty? killed-list ["na"][
  mean killed-list]
end
```

Damage by feral swine has been shown to be a function of density (Hone 1995). Zivin, Hueth, and Zilberman (2000) used a linear function of the number of head present calibrated to deliver the maximum proportion of damage at carrying capacity. Adopting this approach,

$$D_{p,t} = c_J * N_{p,t} \tag{42}$$

where c_J is the damage factor and $D_{p,t}$ lies between zero and one. The damage factor (c_J) is calibrated to set $D_{p,t}$ equal to the damage figure found by Shwiff et al. (Forthcoming) at carrying capacity, J.

The reason that the land user maximizes *expected* utility is because damage is incorporated in the land user's wealth functions stated in equation 25 through 29 in the following equations where M_0 is the agent's initial endowment, $R_{J,p}$ is the parcel specific revenue per parcel for activity J, and $W_{J,p}$ is the parcel specific cost per parcel for activity J. Parcel specific revenue is calculated:

$$R_{J,p} = \xi_p * R_J \tag{43}$$

and parcel specific costs are calculated:

$$W_{J,p} = \frac{1}{\xi_p} * W_J \tag{44}$$

$$M_{t=1} = \sum_{J=1}^{J} \sum_{p=1}^{P} (R_{J,p} * D_{p,t} * a_J^{p,t} - W_{J,p} * a_J^{p,t}) + M_0 \tag{45}$$

$$M_{t=2,3,4,5} = \left(\sum_{J=1}^{J} \sum_{p=1}^{P} (R_{J,p} * D_{p,t} * a_J^{p,t} - W_{J,p} * a_J^{p,t}) + M_{t-1} \right) \tag{46}$$

In the NetLogo model, damage and income are evaluated as part of a single process.

Listing 9: Income Calculation.

```
to go-parcel_NI
  ask patches [
    set parcel_NI (r_corn * damage * a_corn +
      r_soy * damage * a_soy +
      r_huntP4free * a_huntP4free +
      r_huntO4free * a_huntO4free +
      r_huntP4M * a_huntP4M +
      r_huntO4M * a_huntO4M +
      r_CRP * damage * a_CRP -
      c_corn * a_corn -
      c_soy * a_soy -
      c_huntP4free * a_huntP4free -
      c_huntO4free * a_huntO4free -
      c_huntP4M * a_huntP4M -
      c_huntO4M * a_huntO4M -
      c_CRP * a_CRP
        )
; set r_corn r_corn
; set r_soy (Egm_soy + m_soy) * quality
; set r_huntP4free (Egm_huntP4free + m_huntP4free) * quality
; set r_huntO4free (Egm_huntO4free + m_huntO4free) * quality
; set r_huntP4M (Egm_huntP4M + m_huntP4M) * quality
; set r_huntO4M (Egm_huntO4M + m_huntO4M) * quality
; set r_CRP (Egm_CRP + m_CRP) * quality
  ; cost per parcel
; set c_corn (m_corn) * 1 / quality
; set c_soy (m_soy) * 1 / quality
; set c_huntP4free (m_huntP4free) * 1 / quality
; set c_huntO4free (m_huntO4free) * 1 / quality
; set c_huntP4M (m_huntP4M) * 1 / quality
; set c_huntO4M (m_huntO4M) * 1 / quality
; set c_CRP (m_CRP) * 1 / quality
    ]
end

to go-wealth
  ask households[
    set NI-list [parcel_NI] of patches with [owner = self]
   let bb2 sum NI-list
   ; show sum parcel_NI of patches with [owner = self]
    set wealth (wealth + bb2 + a_offfarm * Egm_offFarm) ;sum
        previous wealth and net income form all parcels and off
        farm income
; set utility Eu ; set utility to expected utility
```

```
  ]

end

;;check death
;;households
to check-dealth
  ask households [
    if wealth < 0 [die]
  ]
end
```

The model is under constant development. Even since this writing some processes have been updated.

4 Results

As the model is still under development, these are some of the results demonstrating the progress of the model. Table 3 describes the data created by our BehaviorSpace Experiment. The model was ran for ten years with every possible combination of four different maximum values for each α parameter. This experiment demonstrates that setting the maximum value of α matters. Table 4 shows the results of three different linear regression models. It is important to note that the programming does not choose whether to remove feral swine. The programming sets forth a framework of preferences, and this case sets forth a maximum value of each α parameter. In model 1, the number of feral swine killed in each period is a very good fit with the two hunting preference parameters. The corn preference had no statistically significant relationship. In model 2, the corn preference parameter along with the two hunting parameters was statistically significant in determining the number of patches with corn planted. The third model reveals a problem in reporting. There should be patches with hunting days greater than 180.

In future versions, the land users will begin optimizing over more periods, government will be added and the feedback from one period to the next will be more robust. The key characteristics of agent based models demonstrating interaction between agents will also become more apparent. This version only includes removal of feral swine for utility purposes. Defensive removal is an important behavior that needs to be included.

5 Tables and Figures

Table 1: Summary of Design Concepts By Agent Type.

	Landowners	Government	Feral Swine
Basic Principles	Landowners are complex. They act with several motivations.	Government can be helpful, but isn't always.	Feral swine seek to survive and spread.
Emergence	The primary interest of this model is in how different characteristics of landowners affect feral swine management with the interaction of interest in the model.		
Adaptation	Each year landowners reassess their situation.	N/A	Feral swine move in space away from crowding and removal pressure.
Objectives	Utility Maximization	Maximization of a social welfare function	Survival
Learning	No explicit learning is modeled.		
Prediction	Landowners are forward-looking, with old information. They will maximize utility based on past events and parameters.	N/A	N/A
Sensing	Landowners are aware of feral swine on their property.	Government can sense the utility of its stakeholders.	Feral swine are able to sense removal pressure and crowding.
Interaction	Landowners interact with feral swine by removing them. Landowners interact with each other indirectly by pursuing goals.	Government can indirectly interact with landowners by carrying out policies which may or may not be in alignment with landowner goals and directly with feral swine by removing them.	Feral swine interact with the other agents by moving away from removal pressure, by causing damage, and by providing recreational opportunities.
Stochasticity	Landowners are placed, utility functions are parameterized, and initial wealth is determined by stochastic processes.	N/A	Initial location, removal if they are present on a parcel selected for removal, size of litters are stochastically determined.
Collectives	N/A	N/A	N/A
Observation	Utility is observed and recorded, wealth is observed and recorded. All individuals are tracked even after death or removal. The number of swine removed by individuals is tracked.	The number of feral swine removed by the government is tracked.	A census of feral swine is kept each time period.

Table 2: Notation Table.

Notation	Explanation	Notation	Explanation
i	Index for individual	j	Index for activity
a_j	activity	α	Preference weight for activity j
M_i	Total money available in period t	m_j	Money cost of activity
T_i	Total time available in period t	t_j	Time required for activity
P_i	Total land available in period t	p_j	Land required for activity
λ_T	Shadow price for an additional unit of time	λ_M	Shadow price of an additional dollar
j=CORN	One acre of corn planted	λ_P	Shadow price of an additional acre of land
j=RICE	One unit of rice planted	j=SOY	One unit of soybeans planted
j=WHEAT	One unit of wheat planted	j=PEANUT	One unit of peanuts planted
j=FHUNT-O	Family and friends hunt other species	j=FHUNT-FS	Family and friends hunt feral swine
j=CHUNT-O	Offer commercial hunts for other species	j=CHUNT-FS	Offer commercial hunts for feral swine
j=Offfarm	Hours spent working away from the land.	j=CRP	One unit of conservation reserve program contracted land
Ω	Social Welfare	$E(U_i)$	Expected individual welfare
U_i	Individual Welfare	ϕ	Quantity of government policy
b_ϕ	Cost per unit of policy	λ_B	Shadow price of an additional dollar of government budget
B	Government Budget		

Table 3: Summary Statistics.

Statistic	N	Mean	St. Dev.	Min	Max
X.run.number.	180,224	8,192.500	4,729.667	1	16,384
alpha_corn_i	180,224	37.500	27.951	0	75
alpha_crp_i	180,224	37.500	27.951	0	75
alpha_huntO4free_i	180,224	37.500	27.951	0	75
alpha_huntO4M_i	180,224	37.500	27.951	0	75
alpha_huntP4free_i	180,224	37.500	27.951	0	75
alpha_huntP4M_i	180,224	37.500	27.951	0	75
alpha_offfarm_i	180,224	37.500	27.951	0	75
X.step.	180,224	5.000	3.162	0	10
count.pigs	180,224	54.074	32.389	0	100
count.households	180,224	71.279	28.369	1	166
count.patches.with..a_corn...1.	180,224	238.475	485.084	0	2,401
count.patches.with..a_soy...1.	180,224	588.123	706.565	0	2,401
count.households.with..a_offfarm...0.	180,224	35.095	30.859	0	157
count.households.with..a_offfarm...120.	180,224	32.932	30.522	0	157
count.households.with..a_offfarm...240.	180,224	17.863	21.222	0	141
count.households.with..a_offfarm...360.	180,224	17.863	21.222	0	141
count.patches.with..a_huntP4free...0.	180,224	402.542	625.944	0	2,401
count.patches.with..a_huntO4free...0.	180,224	405.538	629.435	0	2,401
count.patches.with..a_huntP4M....0.	180,224	343.059	602.986	0	2,401
count.patches.with..a_huntO4M...0.	180,224	345.576	602.285	0	2,401
count.patches.with..a_huntP4free....180.	180,224	0.000	0.000	0	0
count.patches.with..a_huntO4free.....180.	180,224	0.000	0.000	0	0
count.patches.with..a_huntP4M.....180.	180,224	0.000	0.000	0	0
count.patches.with..a_huntO4M....180.	180,224	0.000	0.000	0	0
count.patches.with..a_huntP4free.....360.	180,224	0.000	0.000	0	0
count.patches.with..a_huntO4free......360.	180,224	0.000	0.000	0	0
count.patches.with..a_huntP4M......360.	180,224	0.000	0.000	0	0
count.patches.with..a_huntO4M.....360.	180,224	0.000	0.000	0	0
dead.count	180,224	1.416	3.250	0	22
killed.count	180,224	20.219	77.825	0	602

Table 4: Results.

	Dependent variable:		
	killed.count	count.patches.with..a_corn...1.	killed.count
	(1)	(2)	(3)
alpha_corn_i	−0.004	6.997***	
	(0.007)	(0.037)	
alpha_huntP4free_i	0.226***	−2.373***	
	(0.007)	(0.037)	
alpha_huntP4M_i	0.154***	0.415***	
	(0.007)	(0.037)	
count.patches.with..a_huntP4free....180.			
count.patches.with..a_huntP4M.....180.			
Constant	6.082***	49.543***	20.219***
	(0.462)	(2.615)	(0.183)
Observations	180,224	180,224	180,224
R^2	0.010	0.182	0.000
Adjusted R^2	0.010	0.182	0.000
Residual Std. Error	77.448 (df = 180220)	438.777 (df = 180220)	77.825 (df = 180223)
F Statistic (df = 3; 180220)	586.902***	13,350.160***	
Note:			*p<0.1; **p<0.05; ***p<0.01

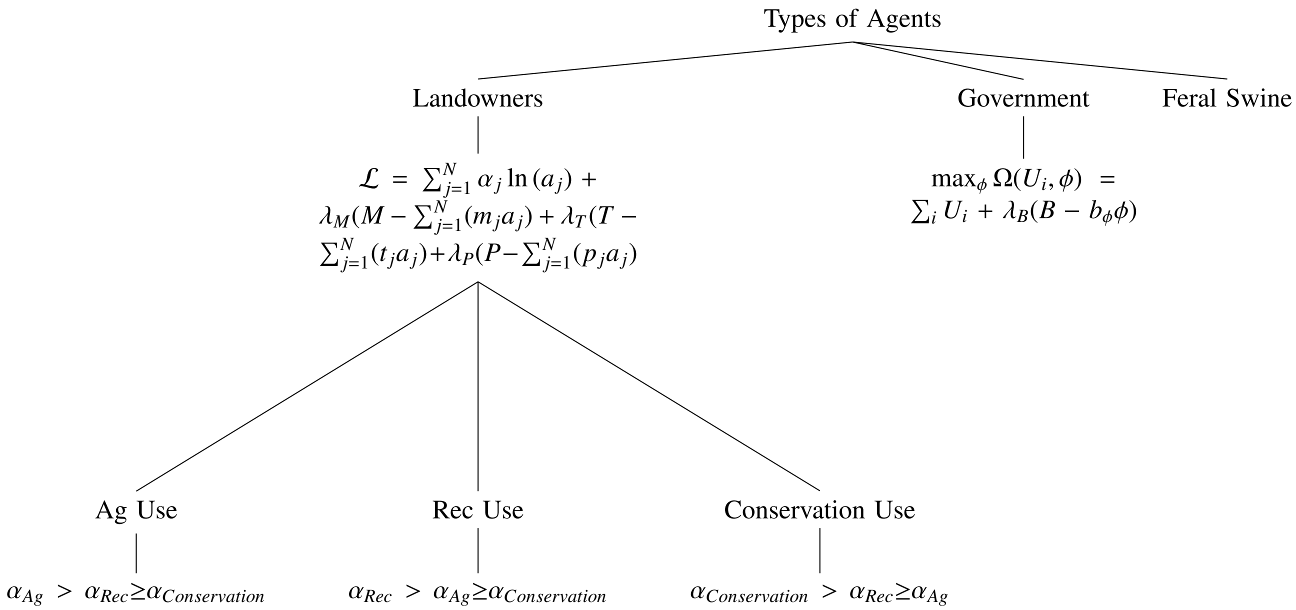

Figure 1: Classification of Agents and Their Objective Functions.

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