Nuggets of Wisdom from Destinations Doomed Due to Dragon Dominion

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Summary

A truly terrifying future may await inhabitants of the Earth: the release of three full-grown dragons. We examine the ecological impacts of real-world dragon introduction, not least to inform fictional literature.

We present a **global agent-based model** to understand the global distribution of dragons and their environmental impact, as well as to evaluate the potential result of human intervention strategies. Three dragons are initialized in the model with individual-level characteristics that contribute to their decision-making and to the ecological havoc that they eventually wreak.

We develop a **regional differential equation model** that zooms in on a single dragon and investigates the dynamics of its growth and impact on prey species and on vegetation cover in its range. Dragons are voracious eaters that will likely prove to be a nuisance for human populations. A likely outcome of dragon introduction event would be management by housing them in zoos, and we calculate the food resources necessary to support dragons held in captivity. Since the caloric requirements of our modeled dragons require them to consume thousands of deer each year, we recommend that the dragons be held to a strict diet to limit their growth.

Our models indicate that releasing dragons into the wild could have disastrous ecological impacts, including the elimination of forests, melting of sea ice, and decimation of prey populations. However, since dragons may provide benefits, such as regulation of nuisance populations and providing resources to humans, careful management could turn the ecology of the situation around. Because of the volatile nature of this problem, we devise multiple complementary models to address it. Our approach may be of value to population managers dealing with similar environmental concerns with real-world nuisance species and human-caused habitat destruction.

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Introduction

Dragons have long captivated the human psyche. From the ancient Near East and Mesopotamia, to the High Middle Ages of Western culture, to the present, dragons repeatedly appear as large reptilian creatures in folklore and mythology [Radford 2019]. Modern audiences may imagine dragons as sinister hoarders of gold and jewels, as depicted in Tolkien's *The Hobbit* [1937], magnificent and perhaps misunderstood in J.K. Rowling's *Harry Potter* series [Rowling 2001], and even alluring suitors of donkeys in Dreamworks's *Shrek* franchise [2019]. While conceptions of dragons have varied with geography and time, the typical dragon in Western culture today is a large, winged, fire-breathing reptile of enormous strength and often capricious temperament, with build ranging from serpentine to *Tyrannosaurus rex*-esque.

In the contemporary hit TV series *Game of Thrones* [Benioff and Weiss 2019], based on George R.R. Martin's fantasy series *A Song of Ice and Fire* [2012], three dragons are raised by Daeneryus Targaryen, the "Mother of Dragons." While the setting of *Game of Thrones* is fictional, its dragons raise the question of whether it could be sustainable to raise dragons on Earth. Dragons from the series tend to favor volcanic mountains as habitats, but the series suggests that they might also thrive in human-dominated habitats.

Problem Statement

We analyze the feasibility of three dragons, based loosely on those in *Game of Thrones*, living on Earth. We analyze dragon characteristics, behavior, habits, diet, and environment. We assess the dragons' ecological impact and requirements, energy intake and expenditures, and land management requirements. We examine these questions in biomes with nine possible distinct temperature and dryness regimes, and we analyze both the impact of dragon migration between biomes and the influence of single-dragon introduction in a particular habitat range.

We assume that the dragons are large reptiles that can fly long distances, breathe fire, and resist attack by other species.

We assume that dragons are born weighing 10 kg and grow to 30–40 kg within a year.

Data Sources and Modeling Approach

We take from the scientific literature physiological data for comparable organisms. We set strict guidelines for dragon growth, reproduction, and feeding. We thus cohesively investigate dragon life history, which could be important to understanding dragon ecology.

We first implement a macroscale agent-based model for dragon expansion across the globe, incorporating constraints on permanent settlement formation ("den" location), energy requirements, habitat destruction by dragons, migration, and reproduction. We then implement a microscale differential equation model of the growth and development of one dragon in a fixed region and its ecological impacts.

Concluding that allowing dragons to roam freely in the wild would be highly detrimental to the environment, we implement a differential equation model for dragons in captivity to gain insight into the support that they would require.

Modeling Methodology

Unique Model Characteristics

We split the globe up into regions of a size reasonable for daily dragon movement; the maximum distance that a dragon can travel in a day is the space of an "ecoregion" cell in model space. Each region is assigned traits, which help or hinder dragon development and reproduction and impact its environment.

Gold-Nugget, Nesting, and Reproduction

In a nod to Smaug from Tolkien's *The Hobbit* [1937], a unique feature of our dragons is that they require gold in order to make their nests. To facilitate this feature, we mandate that each dragon needs to mine for gold.

Once a dragon garners enough gold to produce a suitable den, it settles down and can reproduce either sexually or asexually. Asexual reproduction comes at a greater energy cost, thus is chosen as a strategy only when the dragon is sufficiently healthy and no mates are available.

We assume that all interactions between adult (age ≥ 1 year) dragons can result in sexual reproduction, and we do not distinguish between male and female dragons.

This decision to give dragons multiple reproductive strategies follows from biological phenomena observed in similar reptiles, such as the Komodo dragon.

We assign greater health cost to asexual reproduction but do not enforce that dragons substantially alter their behavior (i.e., migrate) in order to find mates, particularly since we assume that a dragon must settle in a den before it can reproduce.

In our regional differential-equation model, neither reproduction nor gold-mining behaviors are captured, as the primary focus of that model is to understand the ecological impacts and demands of an isolated dragon.

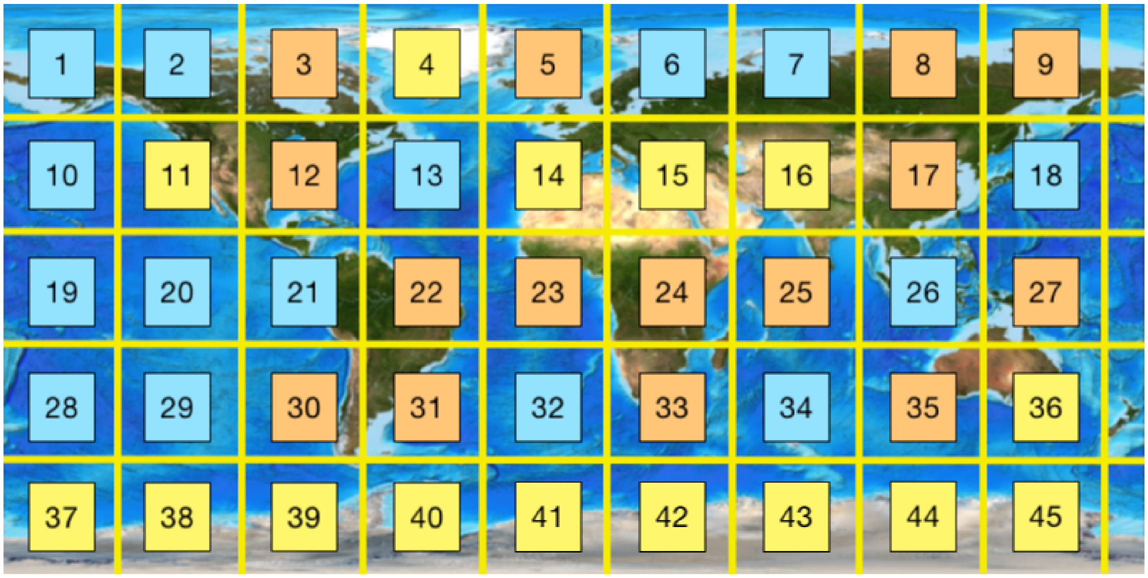

Figure 1. Our partition of the world into 45 ecoregions, coded by dryness (with corresponding regions noted here): blue for a wet climate (regions 1–2, 6–7, 10, 18–21, 26, 28–29, 32, 34), orange for a semi-arid climate (3, 5, 8–9, 12, 17, 22–25, 27, 30–31, 33, 35), and yellow for an arid climate (4, 11, 14–16, 36–45). Credit for underlying map: Wikimedia Commons.

Dragon Prey

We are not specific about dragon prey in our global agent-based model; when we initialize prey, we give them random caloric contents. In the regional differential-equation model, we assume that the dragon, being at the top of the food chain, may eat a variety of prey; however, we refer to all prey animals as "deer" for succinctness and as a nod to the fact that we base the caloric content of prey on deer [Cole 2017].

Agent-based Modeling

Motivation

To model population dynamics of dragons after initial release of three "mature" dragons into random global ecoregions, we use an agent-based model (ABM), implemented as an object-oriented model in Python.

The results inform our later modeling of stress-testing environments under dragon pressure, so as to understand whether intervention measures are necessary.

Mapping

To facilitate movement of dragons across the globe, we divide the world into 45 ecoregions, sized such that a dragon could move from one region to an adjacent one within the course of a day. We assign characteristics to each region, representing factors that would impact dragons.

Earth and Region Initialization

We place three dragons randomly into ecoregions, allowing more than one dragon in a region. We assign each ecoregion

- a dryness rating between 0 and 2 based on the dryness classification shown in the map in **Figure 1**;
- its approximate percentage of land, since we assume that dragons need to hunt over and nest on land;
- its approximate percentage of ice cover, because we are interested in ice depletion due to fire-breathing by dragons;
- a label corresponding to Northern or Southern Hemisphere and climate type; and
- a range of factors to capture the climate and geography of the region, as described in **Table 1**.

Table 1.
Ecoregion parameters and assignment procedures.

Factor	Assignment Procedure	Rationale & Details
Temperature t	tropics = 15, temperate = 5, arctic = 0	Values correspond roughly to average temperatures in °C.
Number d of dens	(den density)× (total land area)	Dens can occur on land, including ice-covered land. Den density is set to 50.
Number n of gold nuggets	(random nugget density)× $\left(\text{total land area} - \frac{\text{ice area}}{2}\right)$	Accounts for fact that ice-covered land is less likely to contain accessible gold. Maximum nugget density is set to 500.
Forest level f	$\dfrac{\text{(total land area - ice area)}}{1 + \text{dryness factor}}$	Does not allow forests to grow on ice and causes drier areas to have fewer forests.
Number p of prey items	Uniform random between 5 and 100	Animal habitation patterns vary.

To each of the p prey initialized in a region, we randomly assign a "calorie content" between 0 and 10. At each timestep, the calorie content of these prey is incremented by 1. When the calorie content of a prey item surpasses 10, it is considered consumed and removed from the simulation. On each day of the simulation, we log the number of prey consumed and calculate a "suitability index" for each region.

The suitability index takes into account the number of dens available, gold nuggets available, number of forests, and the temperature in the region. This index s is calculated as a weighted sum

$$s = \frac{1}{5}\left(\frac{d}{D} + \frac{f}{F} + \frac{t}{T} + \frac{n}{N} + \frac{p}{P}\right),$$

where D, F, T, N, and P are the maximum possible number of dens, the forest level, the temperature, the number of nuggets, and number of prey that can occur in an ecoregion.

Dragon Initialization

We initialize the three original dragons with ages between 1 and 4 years old and weights between 30 and 100 kg, according to uniform distributions. We also give each dragon a health of 100 and a fullness of 5. A dragon that drops to 0 or lower in health is removed from the simulation, and dropping below a fullness of 5 warrants health deductions. Dragons produced via reproduction are born and introduced into the model at 0 years old weighing 10 kg.

Daily Timestep: Globe

On each day, we simulate dragon dynamics in all ecoregions. After we complete the daily timestep function for each of the individual regions, we call a daily statistics function that logs the characteristics of each ecoregion.

Daily Timestep: Ecoregion

On each day for each ecoregion, we define or maintain the seasonal classification based on the local season according to its Hemisphere. We determine the daily temperature for each ecoregion using a calculation that incorporates substantial temperature variation based on climate, yet is realistic :

$$T(t) = \mathcal{U}\big[4S - 4(4 - C),\ 4S\big] + \mathcal{U}\big[C,\ 4.25\big] \cdot S \cdot C,$$

where

- $\mathcal{U}$ is a continuous uniform distribution over the interval indicated;
- S is the season (0 to 1.5 for winter, 2.5 to 4 for summer, and 0.5 to 3.5 for fall and spring), where we perturb the uniform distribution to smooth the yearly temperature curve between the bounds of 0 and 4; and
- C is the climate (0 for arctic, 1 for temperate, 2 for tropical).

In summer (for which $S = 4$), the fact that $S - 4 + C \geq 0$ means that it remains warmer in the tropics in both summer and winter. Maximum temperature is attained in the summer in the tropics; but we never let the temperature exceed 50°C, in keeping with temperature records. **Figure 2** is an example of simulated temperatures in ecoregion 20.

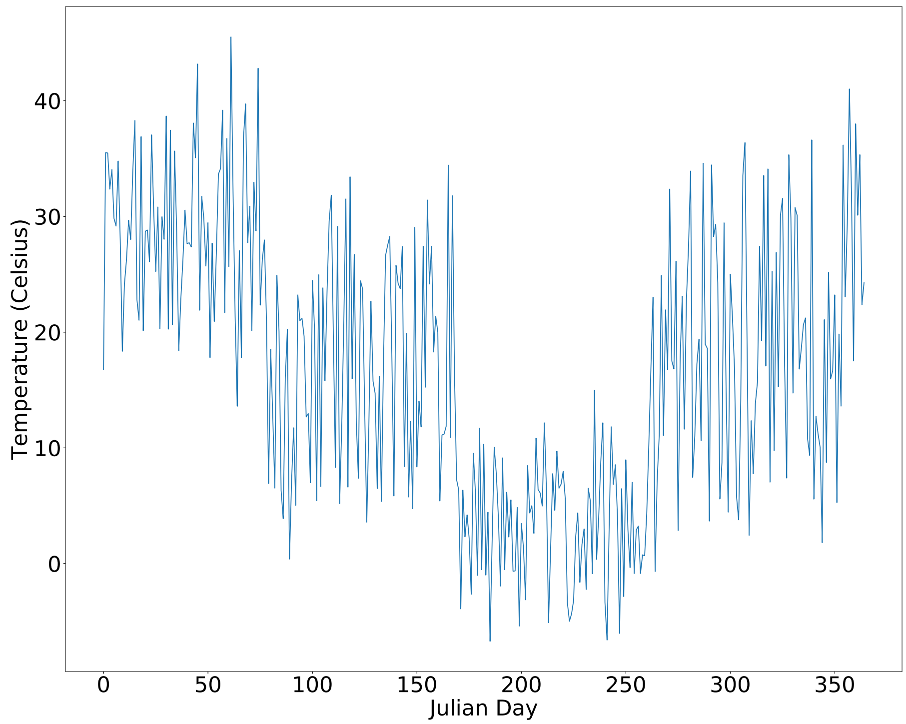

Figure 2. Example of the model's temperatures in a tropical climate in the Southern Hemisphere.

Daily Timestep: Dragon

The age of each dragon is updated by one day, and then the dragon moves through a number of phases:

- **Gold-Nugget Mining** As a first order of business, the dragon mines gold nuggets, for which it requires a minimum health of 20. We calculate the "nugget richness" of the ecoregion as the ratio n/N between the number n of nuggets currently in the region and the maximum number N of nuggets possible in a region. We sample a base number of nuggets to mine from a uniform distribution of size 20 centered around the current health level, and multiply this number by the "nugget richness" to moderate expectations of success. This calculation becomes the number of nuggets that the dragon receives, unless it exceeds the number of nuggets available, in which case the dragon gets all remaining nuggets. Health decreases by 5 after nugget-mining is complete.

- **Den Searching** After gold-mining, the dragon may search for a den if it is currently homeless and has at least 50 nuggets. A searching dragon has a 50% probability of finding a den on each timestep (day). Once a region has no more available dens, a new dragon will need to migrate if it wants to settle permanently.

- **Hunting** Next, the dragon needs to hunt for food to improve its fullness level. The amount of food required is based on a power-law equation for its metabolic functioning, scaled to accommodate the integer rating system that we use to represent the caloric content of prey. Based on Nagy et al. [1999], scaled to appropriate units and forced to take integer values, the predation equation is

$$p(t) = \left\lceil \frac{a[w(t)]^b}{365 \times 5000} \right\rceil,$$

  where a and b are known parameters, $p(t)$ is prey calorie units per day, and $\lceil \cdot \rceil$ is the ceiling function. For each prey item eaten, the "number of forests" is decreased by 1 to account for deforestation due to trampling and fire-breathing associated with hunting. In addition, if ice is present in the region, ice coverage is reduced by 0.1% for each hunting activity performed. The fullness of the dragon increases by the caloric rating of the prey item consumed, and fullness decreases by 5 at the end of each day.

- **Migration** The next decision that the dragon makes is whether to migrate. If the suitability index in its present region is less than 0.1 or if it is eligible for a den but has been unable to find one, it will migrate. A dragon can travel diagonally, horizontally, or vertically to a region adjacent to its current one. Depending on the simulation, we either force the dragon to migrate to the adjacent region with highest suitability index, or we choose with equal probability either that most-suitable cell or a random cell.

- **Reproduction** We assume that reproduction can occur on any given day with 25% probability. Though this may result in frequent mating and reproductive events, we note that many reptile species have large clutch sizes [Rocha et al. 2002]. Because our dragons produce only one offspring per birth, we increase reproduction frequency to better match the fecundity of real reptiles.

  If a dragon's health surpasses 25, and it occupies a den, and its age is $\geq$1 year, it may mate sexually if it can find a suitable mate. Sexual reproduction can occur with any other mature dragon in the same ecoregion, and results in a health deduction of 10 due to the physical demands of reproduction, and in forest and ice loss due to courtship rituals involving fire-breathing.

If sexual reproduction does not occur, and if the dragon has health $\geq$40, a den, and age $\geq$1 year, it can reproduce asexually, which results in a health deduction of 25.

Each day, a dragon's health is incremented by 15 points to reward survival and by an additional 10 points if its fullness surpasses 25. If fullness is between 10 and 25, the dragon gains 0.25 kg, and if greater than 25, 0.50 kg. If a dragon has less than 10 fullness, it loses 0.25 kg if it is at least one year old and weighs at least 30 kg. If it has less than 10 fullness and is less than one year old, it still gains 0.25 kg. If fullness goes below 5, the dragon loses 10 health points.

Table 2.

Actions performed by a dragon, with associated health and environmental costs. Health requirements are the minimum health levels required for the dragon to perform each activity.

Activity	Health Cost	Health Requirement	Environmental Cost
Asexual reproduction	25	40	—
Sexual reproduction	10	25	Land:15; Ice: 0.05 %
Hunting for food	2 per prey	0	Land: 10, Ice: 0.1% per prey
Mine for gold nuggets	5	20	Nugget reduction

Regional Differential Equation Model

To understand on a finer scale the effects of a dragon on an individual region, we design a differential equation model capturing the growth of the dragon and its environmental impact. We assume that

- the ecosystem is stable before introduction of the dragon;
- the dragon—being a very large, potentially very destructive reptile—is the biggest influencer of the ecosystem once it is introduced;
- the dragon is a carnivore at the top of the food chain; and
- since native predators are relatively scarce, once introduced, the dragon is the only predator in the system.

Equations Governing the Dragon

We focus on the dragons mass $w(t)$ in kg, with t in years. We assume that the growth of the dragon follows a logistic growth curve (see **Figure 3**), as in Adolph and Porter [1996], modulated by food availability:

$$\frac{dw}{dt} = r(t)w(t)\left(1 - \frac{w(t)}{w_{\max}}\right)\left(\frac{\text{food available}}{\text{food needed}} - 1\right),$$

where $w_{\max}$ is the greatest weight that the dragon can attain.

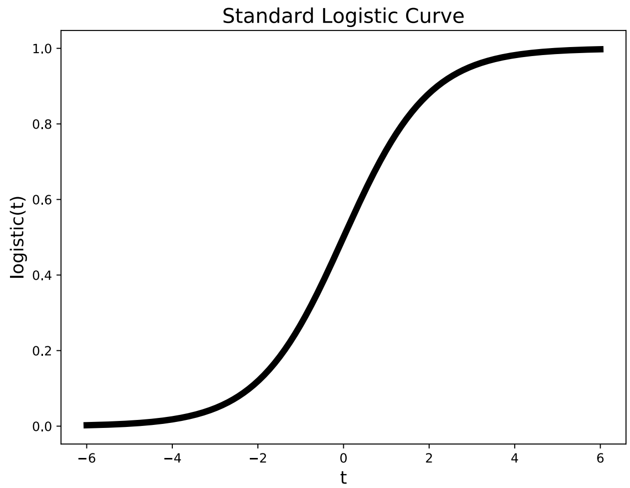

Figure 3. Standard logistic curve $f(t) = \frac{1}{1+e^{-t}}$, satisfying the differential equation $f'(t) = f(t)\big(1 - f(t)\big)$.

We define $r(t)$ to be the dragon's growth rate, which we assume depends solely on the extent to which it can feed. We model $r(t)$ as an optimal growth rate, r_{opt}, scaled by the dragon's level of access to food:

$$r(t) = r_{\text{opt}} \frac{f(t)}{m(t)},$$

where $f(t)$ is the amount of food that the dragon eats in a year, and $m(t)$ is the dragon's yearly caloric requirement. An organism's metabolic requirements can be well-approximated using a power law based on weight, so we assume that the dragon's metabolism $m(t)$ has the form

$$m(t) = a[w(t)]^b,$$

where $m(t)$ is in units of calories per year and a and b are parameters. Nagy et al. [1999] found the values of these parameters to be $a = 139065$ and $b = 0.889$.

The amount $f(t)$ that the dragon eats in a year will depend on how effective it is at hunting and on the availability of prey. We model dragon feeding by interactions between the dragons and prey (discussed below)

$$f(t) = ke(t)p(t)\frac{w(t)}{w_{\max}},$$

where $p(t)$ is the prey level, $e(t)$ is the dragon's hunting effectiveness, and k converts from prey to calories. We include the factor $w(t)/w_{\max}$ so as to increase the dragon's feeding rate as it grows in size. We define $e(t)$ piecewise as linearly increasing until the dragon reaches maturity and then constant thereafter:

$$e(t) = \begin{cases} e_0 + \dfrac{e_{\max} - e_0}{t_{\text{mature}}}\, t, & t < t_{\text{mature}}; \\ e_{\max}, & t \geq t_{\text{mature}}, \end{cases}$$

where t_{mature} is the age at which a dragon reaches maturity. Substituting the expressions above into our expression for $r(t)$, we have

$$r(t) = r_{\text{opt}} \frac{ke(t)w(t)}{w_{\max} m(t)} = r_{\text{opt}} \frac{ke(t)p(t)w(t)}{a[w(t)]^b\, w_{\max}} = \frac{kr_{\text{opt}}}{aw_{\max}}\, e(t)p(t)w(t)^{1-b}.$$

Therefore, returning to dw/dt, we have

$$\frac{dw}{dt} = \frac{kr_{\text{opt}}}{aw_{\max}}\, e(t)p(t)w(t)^{2-b} \left(1 - \frac{w(t)}{w_{\max}}\right) \left(\frac{\text{food available}}{\text{food needed}} - 1\right).$$

Using the conversion factor k between prey and calories, the amount of calories available to the dragon at time t is $kp(t)$. Using the power law for metabolism, the amount of food needed by the dragon at time t is $a[w(t)]^b$, so substituting we obtain

$$\frac{dw}{dt} = \frac{kr_{\text{opt}}}{aw_{\max}}\, e(t)p(t)w(t)^{2-b} \left(1 - \frac{w(t)}{w_{\max}}\right) \left(\frac{kp(t)}{a[w(t)]^b} - 1\right).$$

Writing $c = k/a$, the differential equation has the form

$$\boxed{\frac{dw}{dt} = \frac{cr_{\text{opt}}}{w_{\max}}\, e(t)p(t)w(t)^{2-b} \left(1 - \frac{w(t)}{w_{\max}}\right) \left(c\frac{p(t)}{[w(t)]^b} - 1\right).}$$

Equations Governing the Environment

In addition to the growth of the dragon, we are interested in its impact on the environment. We assume that dragons are carnivores at the top of the food chain, they eat "deer," and other predators are insignificant in light of a massive, murderous, meat-eating monster from Middle Earth [Tolkien 1937]. We model the availability of prey $p(t)$ with a simple predator-prey model:

$$\boxed{\frac{dp}{dt} = jp(t) - e(t)p(t)\, \frac{w(t)}{w_{\max}},}$$

where j is the natural population growth rate of prey and $e(t)$ defines dragon's hunting effectiveness (discussed previously). Since we are modeling interactions between deer and just one dragon, rather than a group of dragons, we scale the interactions by the dragon's weight, such that more massive dragons eat more deer.

Dragons may cause environmental damage by trampling vegetation and breathing fire as they hunt, and we assume that they are the main source of environmental degradation in our system. Letting $v(t)$ denote the proportion of the dragon's environment that is covered in vegetation, we model vegetation growth and damage by

$$\boxed{\frac{dv}{dt} = \ell v(t) - g\frac{w(t)v(t)}{w_{\max}},}$$

where g is a parameter representing the frequency of dragon-damage and ℓ represents the natural growth rate of the vegetation.

Equilibria

We perform a stability analysis on the system of differential equations. Since dw/dt and dp/dt do not depend on v, we determine equilibria for just w and p:

$$\left\{(w,0),\ \left(\frac{jw_{\max}}{e(t)},\ \frac{1}{c}\left(\frac{jw_{\max}}{e(t)}\right)^b\right)\right\}$$

The first point is the zero solution and not of interest, so the second is the only nontrivial equilibrium point of the system.

Parameter Identification

Table 3 describes each parameter in our model, its interpretation, and initial values chosen based on outside literature or desired model characteristics.

Model Results

Agent-Based Model

Without Resource Controls

When we run the agent-based model without resource controls on the dragons (i.e., dragons are not affected by the decimation of the environment but prey are), not many dragons remain by the end of the simulation and the environment becomes severely depleted. However, if we mandate that dragons stop expending health on nugget-mining after finding a den, we get much greater dragon populations.

Table 3.
Parameters of the models.

Parameter	Interpretation	Initial Value	Rationale
$c = k/a$	$\frac{\text{calories per deer}}{\text{calories needed by dragon per (kg of mass)}^b}$	$\frac{119040}{139065} = 0.856$	Based on calories available in a deer [Cole 2017] and on reptile growth rate [Nagy et al. 1999]
r_{opt}	Optimal dragon growth rate	0.035	Chosen such that weight is 30–40 kg at one year of age, as per problem statement
$w_{\max}$	Maximum dragon weight	6000 kg	Dragon is roughly as heavy as an elephant
b	Exponent in metabolic power law relationship	0.889	Nagy et al. [1999]
j	Population growth rate of prey	0.25	Chosen to be high
ℓ	Vegetation growth rate	0.09	Situationally dependent
g	Dragon destructiveness	0.2	Dragon is 20% destructive, due largely to fire-breathing
e_0	Dragon's initial hunting effectiveness	0.1	Chosen so that baby dragons are bad hunters
$e_{\max}$	Mature dragon's hunting effectiveness	0.5	Dragons can't be *that* good at hunting; they are very large predators seeking relatively small prey
t_{mature}	Dragon age of maturity	21	A dragon is an adult only once it can legally drink. (!)
w_0	Dragon weight at birth	10 kg	Problem statement
p_0	Initial prey species population	5,000	Corresponds to $\sim$45 deer/square mile over 111 square miles
v_0	Initial proportion of ground covered by vegetation	0.5	Represents suburban/ urban area

Resource Controls on Prey Proliferation: Forest Removal

In the above simulations, we use the suitability index of the region to determine whether additional prey would populate each ecoregion. If we multiply the prey produced in each interval by the forest fraction f/F, we can simulate the effect on prey species of the loss of forest. Doing so does not cause a rebound in dragons subsequent to initial declines due to low suitability indices. Instead, the dragon populations quickly decline, but the forests do not suffer as dramatically.

The Influence of Gold-Nugget Mining

Similarly, if we mandate that dragons stop gold-nugget search after finding a den, the environment improves dramatically; notably, the ice no longer disappears from Antarctica.

Conservation Intervention Simulation

Our simulations lead us to conclude that dragons released into the wild cause complete destruction of the ecosystems best for them (warm climates with forests containing ample prey species). In response to this issue, we implement conservation measures in our model.

- We simply reforest depleted areas, that is, restore the forest levels by the amount lost whenever forest losses surpass a defined threshold.
- We simulate humans taking hunting dragons, that is, we take out one dragon from each region in each timestep.

The threshold value for forest loss plays a major role in the final number of dragons present in the population, but only up to a certain point (restoration after about 10% of losses in the maximum scenario). This is because dragon removal too early prohibits dragon proliferation.

Regional Differential Equation Model

We perform a regional differential equation simulation using our initial parameter values to understand the dynamics of the ecosystem and gain information on energy requirements. Additionally, we do a range of parameter studies in order to understand how a dragon responds to environmental conditions and growth rates. All simulations use the forward Euler method with a time step of one month, unless otherwise noted.

Initial Results

Figure 4 shows graphs of the weight of a dragon, the prey level, the vegetation level, and the dragon's metabolism, over a 50-year period.

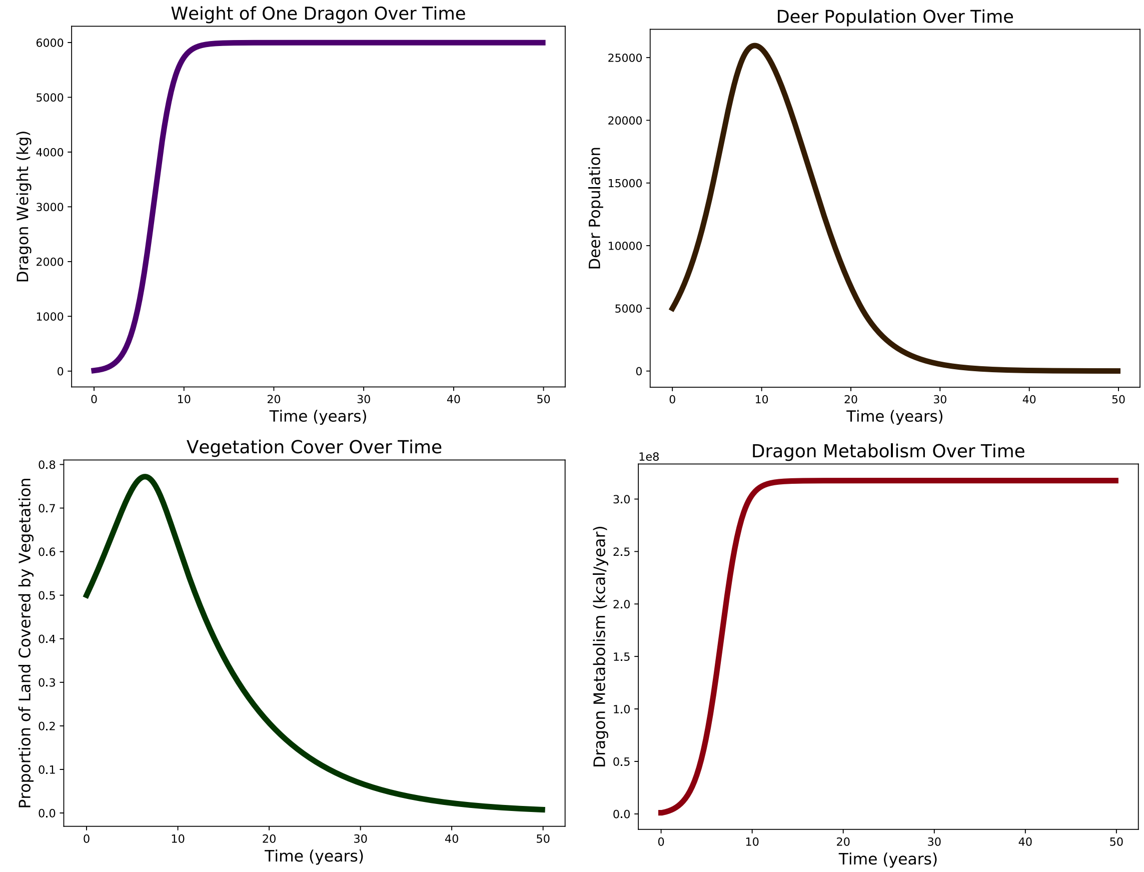

Figure 4. Dragon growth, deer population, and vegetation cover for original parameter values.

The dragon nears its target weight of 6,000 kg within 10 years. Due to the dragon's high growth rate and consequent consumption levels, the deer population, which during the dragon's infancy spikes from 5,000 to almost 25,000, is decimated within 30 years, and after 50 years is at a mere 3 deer. The area's vegetation levels fare similarly poorly due to the dragon's fiery disposition. Responsible for this devastation is the dragon's voracious appetite, which scales with its size. As an infant, the dragon's metabolism is 1 million calories (9 deer) per year. By the time the dragon reaches 12 years of age, it requires 315 million calories (2,600 deer) per year. The dragon continues to require deer at this alarming level for the rest of its life, causing utter population destruction.

Parameter Studies

We vary each parameter to see the effect on the dragon's development and on the environment.

- **Caloric ratio** $c = k/a$

  The parameter $c = k/a$ is the ratio of the number of calories in a single deer to the calories required by a dragon per (kg of body mass)^b. Varying c has marked effects on dragon growth outlook and on the deer (see

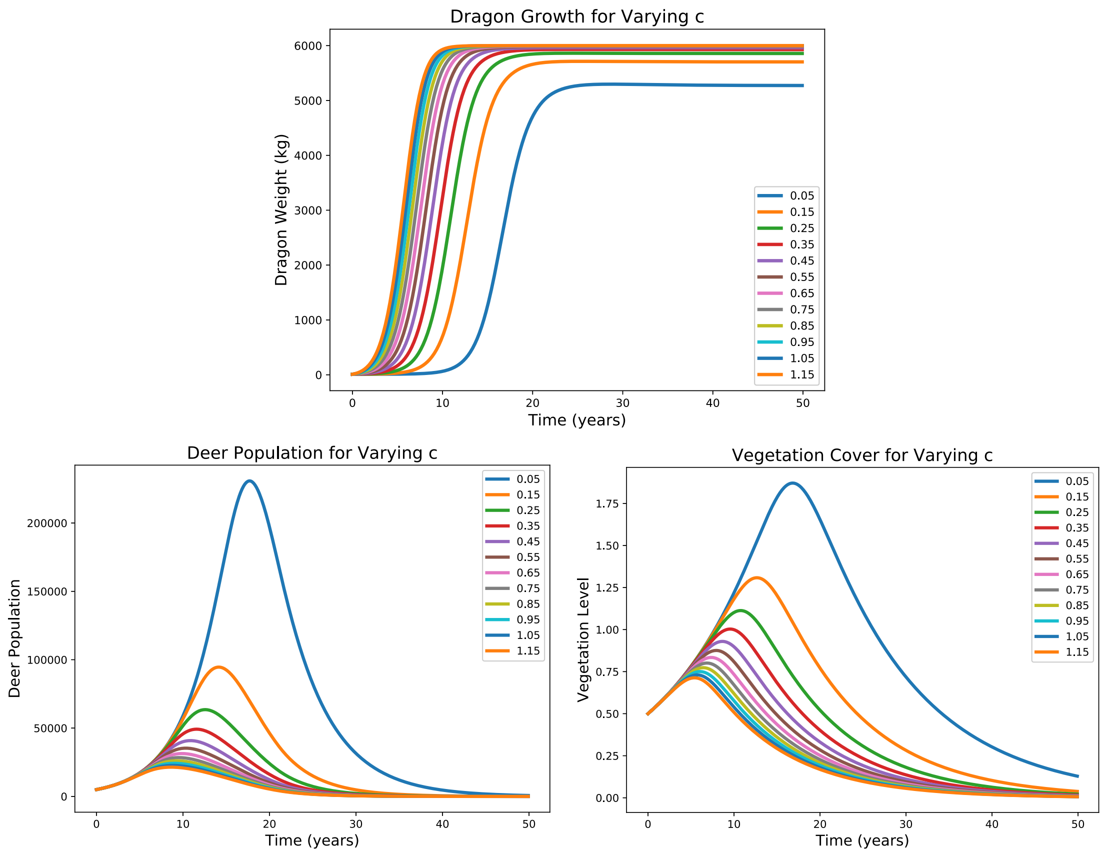

Figure 5. Dragon growth, deer population, and vegetation level for various values of c.

Figure 5). For low values of c, the dragon grows slowly and has a hard time reaching its target weight, indicating that dragons would struggle to fare well in the absence of high-calorie food sources. The deer, on the other hand, experience higher population spikes when they provide less sustenance to the dragons; but in all scenarios, they eventually die out. Vegetation levels follow patterns analogous to the deer population.

- **Initial deer population** p_0

  A dragon suffers with low initial deer populations (less than roughly 2,250) and has a hard time reaching its target weight. Adding deer to the initial herd beyond 2,250 does not significantly impact a dragon's final weight but allows it to reach it faster.

  Conversely, for the deer, it does not appear that there is safety in numbers. Even though deer herds with higher initial populations spike to the highest peak populations, this spike occurs early and they begin to decline rapidly. Herds with lower initial populations last longer before experiencing this decline, and they have higher populations during the decline compared to herds with higher initial populations. Vegetation is also more successful with lower initial deer populations, with vegetation cover having the highest peak and declining the latest for lowest levels of deer population (see **Figure 6**).

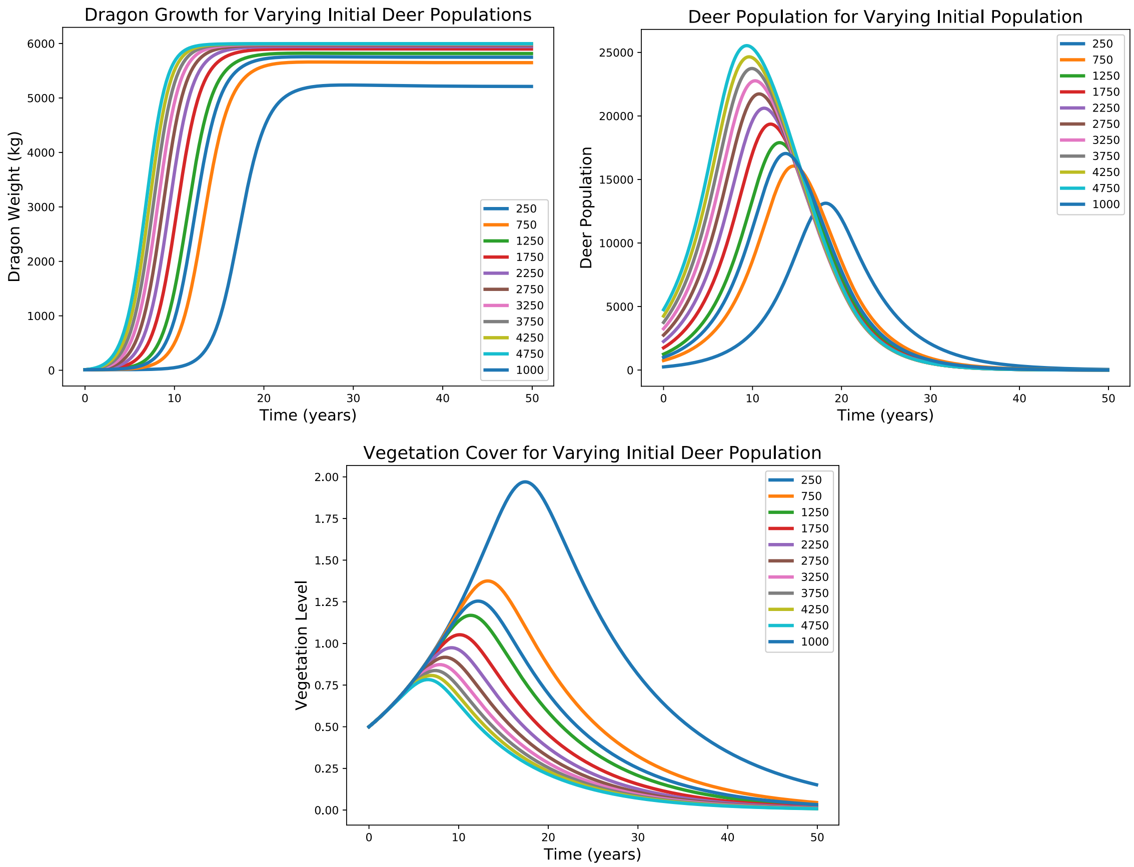

Figure 6. Dragon growth, deer population, and vegetation cover for various values of p_0

- **Dragon destructiveness g**

  Although the dragon destruction parameter g does not affect growth of the dragon or of the deer population, we notice an interesting bifurcation in vegetation stability when we vary g between 0.001 and 0.5 (see **Figure 7**). For values of $g \leq 0.05$, the vegetation does not get decimated as observed previously, but exhibits almost nonsensical exponential growth. For values of $g \geq 0.1$, vegetation decay falls to almost nonexistent levels, as before. This phenomenon suggests that dragons that are only moderately destructive can peacefully coexist with the environment without torching it all to charcoal.

- **Maximum hunting effectiveness $e_{\max}$**

  Changes in $e_{\max}$ don't have drastic effects on the dragon's growth or the vegetation cover but do so on the deer: For $e_{\max} \geq 0.3$, the deer eventually die out, albeit at slower rates for lower values; but for $e_{\max} = 0.2$, the deer population increases exponentially, even though the dragon doesn't seem to be adversely affected see **Figure 8**). This result is hopeful, since it demonstrates that the deer herd can endure if a dragon is bad at hunting but the dragon isn't too adversely affected by its poor hunting skills.

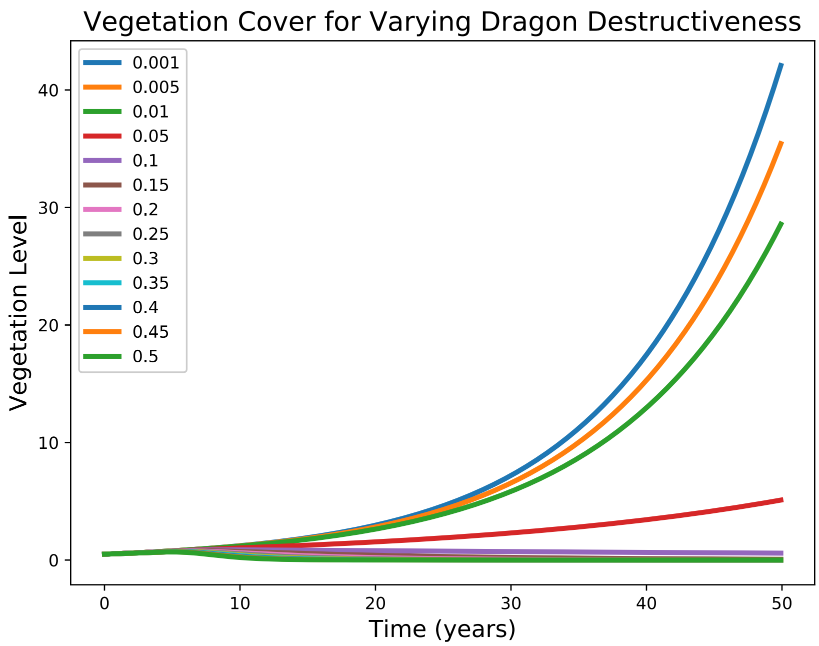

Figure 7. Vegetation cover for various values of g. There is a bifurcation point, affecting the stability of the vegetation population, between $g = 0.05$ and $g = 0.01$.

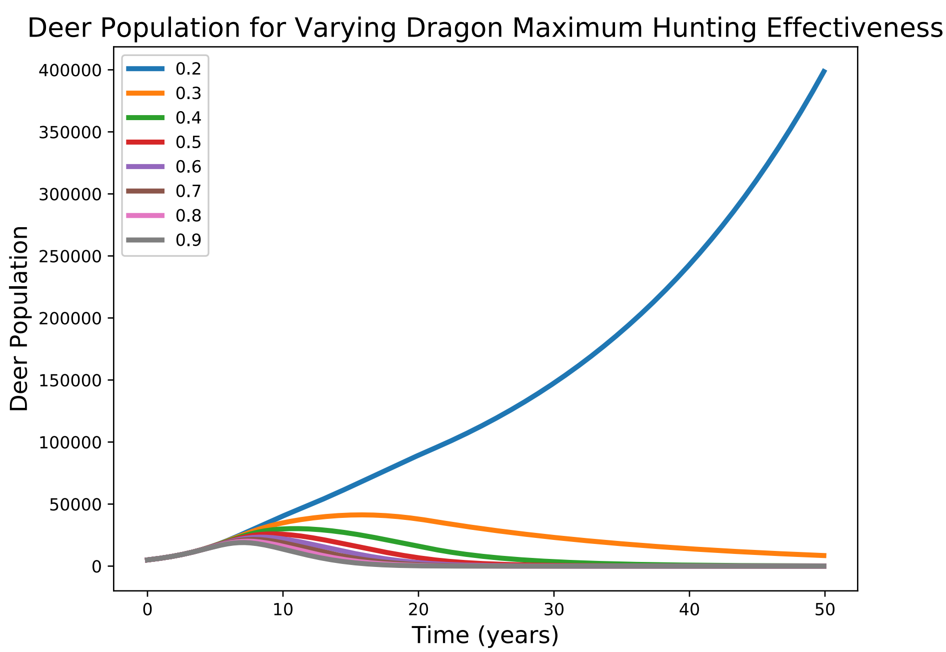

Figure 8. Deer population as a function of dragon hunting effectiveness.

- **Deer population growth rate j**

  The deer population growth rate j has a substantial effect on the dragon's growth, with low values of j causing the dragon to grow to less than one-third of its target weight (see **Figure 9**). For j <0.05, the dragon grows to less than half of its weight, and j must be at least 0.15 for the dragon to even reach 5,000 kg (83% of its target weight). As expected, the deer die off quickly with low deer population growth rates; and due to the devouring dragon, the only value of j tested that produced a non-negligible deer population at the end of 50 years was $j = 0.45$, which is quite high.

  These results indicate that if the deer population growth cannot keep up with the dragon's growth, the dragon will suffer and the deer will perhaps suffer more. Additionally, we observe an interesting bifurcation in vegetation behavior around $j = 0.05$. For $j \leq 0.05$, the vegetation flourishes, because the deer aren't multiplying enough to feed the dragon, so it doesn't become as destructive as it would normally.

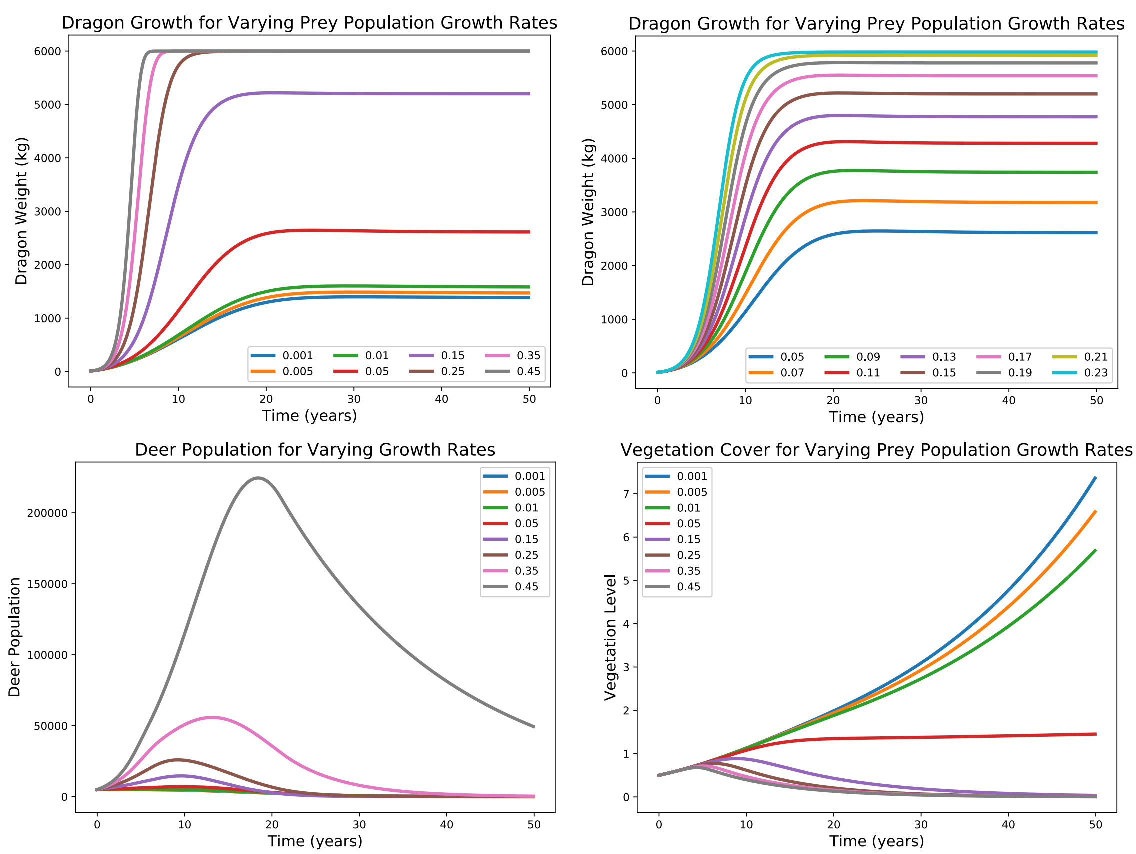

Figure 9. Dragon growth for $j \in [0.001, 0.45]$, dragon growth for $j \in [0.05, 0.23]$, deer population for $j \in [0.001, 0.45]$, and vegetation cover for for $j \in [0.001, 0.45]$

- **Dragon maximum weight** $w_{\max}$

  While changing $w_{\max}$ produces very predictable changes in the dragon's growth, of note is the fact that of all values of $w_{\max}$ tested, even the smallest of dragons (with the lowest of metabolisms) still exterminates the deer population and destroys the vegetation (see **Figure 10**).

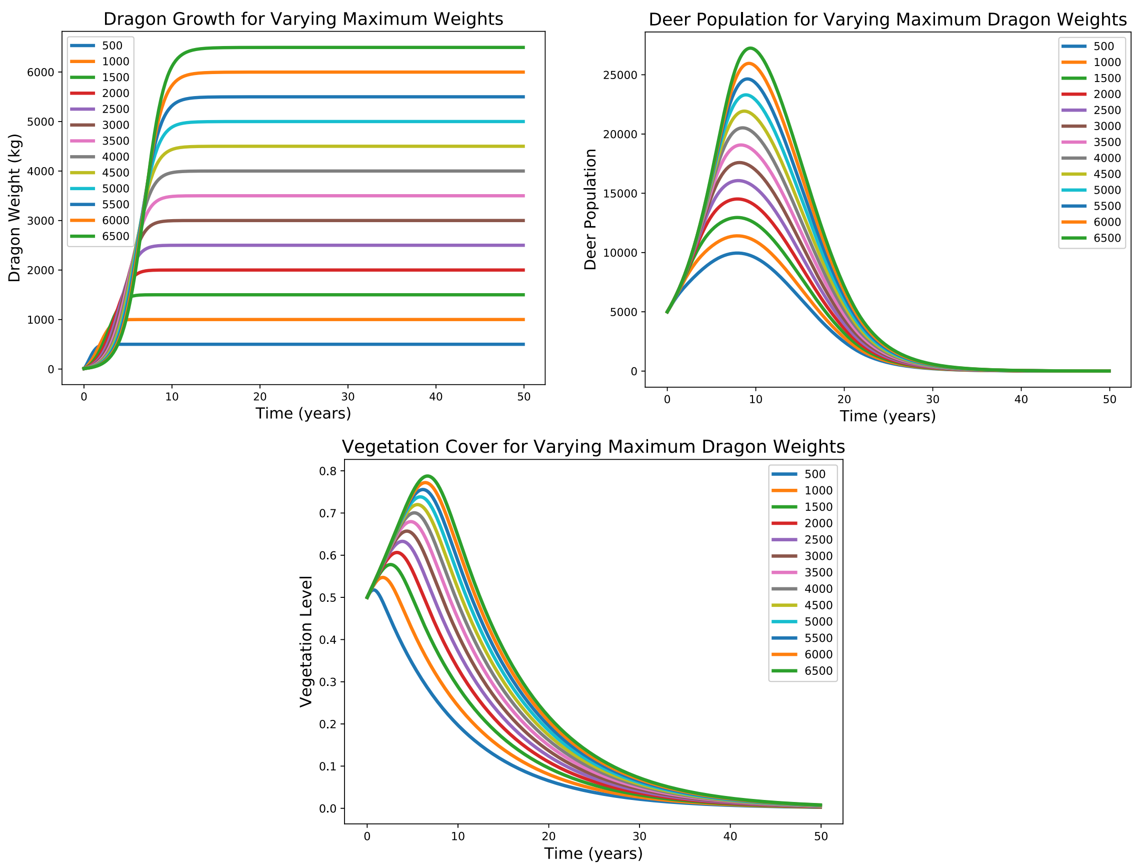

Figure 10. Dragon growth, deer population, and vegetation cover for various values of $w_{\max}$

Dragons Kept in Zoos

Dragon-related damage to the environment seems inevitable, so we explore an alternative fate for the dragons: After dragons proliferate naturally or are bred in captivity, intervention would keep them alive but away from fragile ecosystems.

Supporting a single dragon up to 6,000 kg in weight could require a deer population of thousands. Given that the average whitetail deer may have a home range of 2 miles [Barringer 2016] or 907 acres [Thomas 2014], it is unreasonable to suggest that a zoo could support a deer herd of sufficient size if deer were supplied naturally. Much like management of zoo populations for naturally-occurring animals, it would be necessary to consider how to alter the feeding patterns and living conditions of dragons to suit life in captivity [Derr 2003]. Even if animals are allowed to hunt naturally in their habitat, it is unlikely that the dragons, which we have thus far been modeling as traveling very large distances, would be happy in a small enclosure. Additionally, zoos already spend millions of dollars each year on feeding programs [Pressler 2011]. If a dragon were to be housed in a zoo, care would have to be taken to manage its diet so that it did not grow past a certain size and could be managed in captivity.

Using the components of our regional differential equation model, we modeled the number of deer needed each year to sustain a dragon at different maximum weights (**Table 4**). We also present in **Figure 11** a sample curve for deer/calories consumed per year over the first 15 years of the dragon's life. These estimates are within range for animals of similar size; for example the African elephant has an estimated yearly caloric budget of 26 million calories [San Diego Zoo n.d.].

Table 4.

Number of deer or amount of calories needed each year at different maximum dragon weights over a 15-year period. Minima are based on metabolic rates and maxima are based on observed feeding in the wild, which is modulated by prey availability.

Max Weight (kg)	Min Deer/yr	Min Calories/yr $\times 10^8$	Max Deer/yr	Max Calories/yr $\times 10^8$
250	158	0.1	2627	3.1
500	293	0.4	2793	3.3
1000	543	0.7	3200	3.8
2000	1005	1.2	4074	4.8
3000	1441	1.7	4954	5.9
6000	2666	3.2	7507	8.9

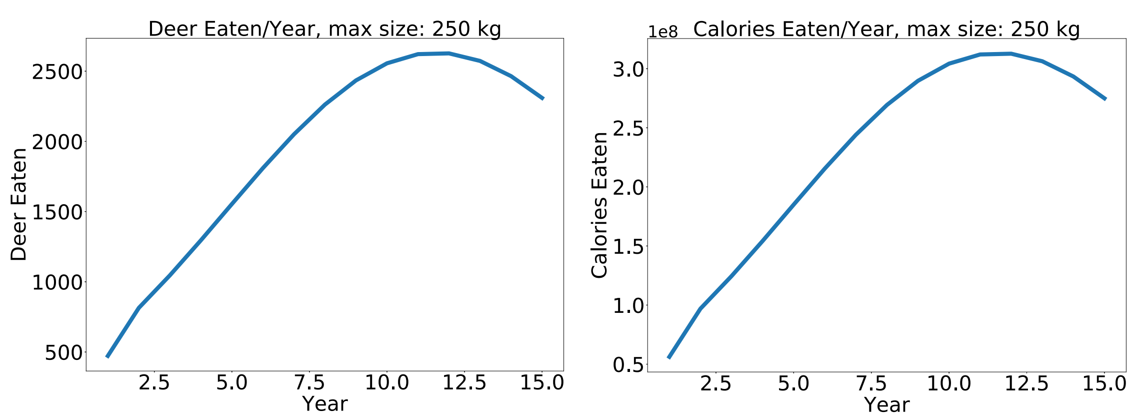

Figure 11. Deer (left) and calories (right) needed at maximum each year for a dragon whose weight is capped at 250 kg.

Model Analysis

Agent-Based Model (ABM)

Model Strengths and Insights

Our ABM allows us to evaluate global scenarios of dragon population expansion without being overly specific about the ecological niche that the dragons will adopt.

- Our model shows that the most likely scenario is that dragons will congregate in the most suitable habitat for them.
- Despite this grouping, dragons are likely to wreak havoc on the environment no matter how long they occupy a region, due to their rapid migration and destructive habits.
- Human intervention can have a considerable influence on the size and on the effects of the dragon population. Using our ABM, we can evaluate human-dragon interaction at the macroscale, which is particularly important given our speculation that dragons may become a valuable game species.
- Our ABM allows us to consider a general prey species, and requires that we set the regeneration rate of prey to be fairly high to accommodate the dragons. This may be an overly optimistic environment for the dragons, but we could easily tune changes in prey availability in accordance with improved understanding of dragon physiological demands (as well as new knowledge about the extent to which the creatures hunt for recreation).

Climate Factors

While habitat suitability plays a major role in the population distributions observed, this is highly dependent on whether we assume that dragons form permanent nests. In our initial agent-based model runs, we observed that while the suitability of the regions quickly decreased, the regions with the highest suitability scores still supported the highest dragon populations later due to legacy nesting. This effect decreases if the number of available nests is decreased or if the need of the dragons to form permanent nests is reduced or eliminated.

Model Limitations

While our ABM allows us to understand long-term global dragon dynamics in relation to climate and geography and incorporates stochasticity, there are some major limitations of the approach. These limitations, which inspired our adoption of differential-equation modeling approach to fill in the gaps, include:

- Our model is unable to appreciate the changing habitat requirements of growing dragons. No matter how big the dragons get, we do not consider range expansion beyond a single ecoregion.
- The assumption that dragons live in dens makes it impractical to consider expanding a dragon's home base. Because dragons are limited to the den in which they reside, they may be isolated geographically from other dragons.
- The assumption that each den is a uniform unspecified size does not allow for the possibility of dragons outgrowing their homes. In response to this, in one version of the simulation, we limit dragon growth after a certain size until it obtains additional gold nuggets. This approach enables us to see how the dragons might be physiologically limited by their physical environment outside of food issues.
- A pressing concern left out of the model is encroachment of dragon populations on human populations. We do not take into account either physical/territorial altercations between dragons or their potential interactions with humans that fall outside the realm of resource consumption. While we explore the result of human intervention for conservation purposes, we do not consider the social pressure associated with a growing dragon population. It is possible that safety concerns could lead to human demand for dragon population control. However, we address this scenario via a zoo management scenario.

Regional Differential Equation Model

Model Strengths and Insights

Using differential equations to model the impacts and demands of one dragon in a specific region allows us not only to observe dragon growth and environmental damage under a specific set of reasonable parameter values, but also enables us to understand the dragon's and the environment's responses to variations in these parameters. Some conclusions of note are:

- The caloric demands of a dragon are very high and scale with its weight, which in all simulations increase very rapidly. We encounter very few scenarios in which the prey herd size and growth rate are sufficient to avoid eventual extinction of the dragon.
- A dragon's final weight is very sensitive to the growth rate of its prey, requiring an annual prey growth rate of at least 15% to reach even 83% of its target weight. The prey, however, do not benefit from the suffering of

the dragon; they are all eventually eaten even when the dragon's growth is severely stunted.

- Prey growth rates (and herd sizes, which also affect the dragon's growth) can be viewed as corresponding to environmental conditions of varying harshness. Dragons may do poorly in cold or arid environments where prey is scarcer or is replenished at a slower rate.
- The deer are devoured and the vegetation vanquished by the dragon in almost all of our parameter studies, suggesting that a dragon in the wild would be extremely destructive. Although there are a few instances in which the deer and/or vegetation endure, these are rare, and couldn't be counted on to occur under real-world settings. Hence, we do not recommend letting dragons run amok unchecked in the wild, but propose strategies for controlling them.

Model Limitations

While we can perform substantial analysis on our model in its present form, there are areas which we wish our model could address more precisely and in which improvements could be made:

- The regional differential equation model is not impacted by the size of the region, since it accounts only for the size of the deer herd present and the vegetation coverage rate. Interactions between dragons and deer would likely increase with higher deer density, but we are unable to capture this in our model.
- While the dragon majorly impacts vegetation levels, the dragon and the prey experience no adverse effects from environmental degradation. While the dragon is certainly the main driver of deer destruction, this simplification may not be realistic because destruction of habitat would lead to a decrease in available prey, which would in turn cause less food available to the dragon.
- We vary only one parameter at a time in our parameter studies.
- The equilibria of the system are not physically meaningful, aside from the trivial solution (no dragons, etc.).

Real-World Applications

Although our analysis concerns a fictitious dragon species, our approach could be of use to population managers in the real world. Our dragons are large reptiles that require a significant amount of resources and are highly mobile, and these characteristics match to some extent other known animal species. The parameters of our model could also be modified to correspond to animals much different from dragons; and while the globe is an atypically large scale for an agent-based model, a global ABM could be appropriate for some species, e.g., whale sharks [Sequeira et al. 2013].

The predatory nature of the dragons can be seen as a double-edged sword: On the one hand, it poses serious threats to prey populations; but on the other hand, it could aid in the elimination of nuisance species. For deer, the prey animal that we base our analysis on, much focus has been placed on managing their numbers for the purposes of reducing tick transmission and automobile accidents [Conover 1995; Jordan et al. 2007; Romin and Bissonette 1996]. Our approach could be used to model a real predator serving as moderator of deer populations for human benefit, or to model deer populations under scenarios of human management. Modeling a territorial animal could be useful for understanding species that tend to nest for life and do not have the need to reproduce sexually, namely, to track their global distributions and enable conservation strategies [McLane et al. 2011]. In the face of climate change, ABM techniques can reveal differential clustering of species based on their reproductive rate under particular conditions and with certain habitat preferences [Moss et al. 2001].

Conclusions

Using both a global agent-based model and a regional differential equation model to simulate potential dragon dynamics, we find that the consequences of releasing dragons into the wild are indubitably dire.

With our ABM, we find that the most likely outcome of dragon release is settlement in—and subsequent devastation of—the ecoregion involved. If dragons are allowed to multiply unchecked, this environmental devastation inevitably spreads to most of the globe. In response to this outcome, in later iterations of our ABM we simulate population control and environmental restoration by humans and find these measures to be somewhat effective at curbing dragon-caused calamity. However, small changes to the model, such as the timing of the onset of human intervention, have relatively drastic implications for dragon population size and the ecological impact of the dragons, including resource consumption and ice melt.

With our differential equation model, we simulate dragon and environmental responsiveness to changes in parameters controlling dynamics of the system. In particular, we find that the predator-prey system is particularly sensitive to the growth rate of the prey, which dramatically impacts a dragon's final weight. Simulations lead us to the conclusion that because the caloric demands of a dragon are so high, the peaceful coexistence of a dragon and an existing ecosystem is impossible. Dragons have monstrous appetites and cause catastrophic ecological damage, even independent of their tendency to rampage the environment with fire breath while hunting.

Because our approach captures both the spatial elements of dragon proliferation via the agent-based model and the fine-scale ecological interactions of each dragon via the differential equation modeling, we can make balanced recommendations for management, including human hunting and zoo-based management. In almost all scenarios explored for both the global agent-based model and the regional differential equation model, the dragons cause massive environmental devastation, including the melting of sea ice in addition to deforestation and extinction of prey species.

In light of these dismal results, we adamantly advise against the release of dragons into the wild unchecked. Alternative strategies for hosting a dragon population could include captivity in zoos, which would require enormous resources, including hundreds to thousands of deer per year (and potential animal-rights concerns), or a well-managed dragon-hunting season (contact the corresponding author for tasty dragon recipes). For the purposes of George R.R. Martin's imagination, however, the possibilities are endless (and, quite possibly, satisfying, even where irresponsible).

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Letter to George R.R. Martin

George R.R. Martin
Super Secret Medieval Lair
Santa Fe, NM

Dear Mr. Martin:

Our team has conducted an analysis regarding the likely outcome if the three fictional dragons from *Game of Thrones* were to be released into the world, encompassing their prey requirements, land-use strategy, and reproductive success. We base our modeled dragons on your *A Song of Ice and Fire*, with some notable modifications to accommodate the likely needs and preferences of fictitious dragons released into the real world.

We present you with some recommendations how you might incorporate into your next story some elements of this fiction-meets-reality.

To begin, we devised an agent-based model that randomly places three dragons, with semi-randomly assigned characteristics, somewhere on the globe, which we represent as a series of 45 connected regions. We assigned the 45 map locations dens in which dragons could nest.

It quickly became apparent that dragons might gravitate toward semi-arid or tropical regions, given an assumed preference of these cold-blooded creatures for warmer climates and ample availability for nesting. Dragons are unlikely to be able to live for long periods of time in arctic regions, due to the requirement for prey; but they are more likely to find a home in wetter, more temperate climates as opposed to arid regions. Given dragons' requirements for prey, and our requirement that mature dragons must locate gold nuggets in order to settle in a permanent den, natural resource and prey availability quickly emerge as important constraints on dragon growth and population expansion.

Through our agent-based model, we find that the habitat range of dragons tends to be relatively limited, and that dragon populations—if left unchecked—tend to completely rob a region of its natural resources. For this reason, if you choose to write a story on the real-world implications of dragon escape, it is likely that you will need either to imagine a post-apocalyptic world or to design a mechanism through which humans can manage the dragon population. In our model, we include the potential intervention strategy of people removing a maximum of one dragon from each region each day in response to habitat destruction imposed by the dragons. People are also able to restore some of the removed forest habitat in our model.

We explored both the baseline ecological impacts of dragons and the potential interactions that humans might have with them. To gain an understanding of the impact that a single dragon might have on a region, we designed a differential equation model to simulate the lifespan of a dragon and its impact on prey species (assumed to be deer) and local vegetation. We found that, in order to grow to full size, there must be an ample supply of deer and the dragon must be somewhat good at hunting. Specifically, there must be a sizable herd of deer initially, and they must multiply at 15% per year or more in order for the dragon to have enough food to eventually reach at least 83% of its target weight. We computed the caloric demands of a dragon using a power law and find that a fully-grown 6,000-kg dragon (the mass of an elephant) needs to consume at least 2,700 deer per year to sustain its metabolism. Since a high estimate for deer density would be 45 per square mile, a dragon would need at about 60 square miles of land to have enough deer for a year—and then it wouldn't have any left for the next year. Although we are supportive of the flourishing of dragons, unfortunately, in most scenarios, these ruinous reptiles decimate the deer and evict the vegetation in the areas they inhabit.

Since the energy requirements for a dragon are so great and the ecological impacts so dire, we find it probable that dragons would not be allowed to run amok in the wild, but rather would be kept in captivity. This could be an interesting plot element in your story that is a realistic outcome, but it requires that you set your story in modern times. We propose that dragons, either before or after initially wreaking havoc on global ecosystems, could be kept in zoos. A dragon in captivity restricted to only 250 kg in eventual size would require 160 deer per year, vs. 2,700 in the wild. This would be a tremendous investment in the care of each animal, possible for only the world's largest zoos, and would also present an animal-rights question if the dragons were provided only the bare minimum. The spectacle of an in-house dragon would be a significant attraction for a zoo; the high concentration of people there would be perfect for a plot twist involving some dramatic action terrorizing the crowd.

We also posit that dragons could become part of human culture by serving as a food source, in addition to their ecological role in managing extremely large prey populations. This would be a particularly interesting plot element in a story set in medieval times. We find through our modeling that dragon populations have the potential to grow substantially in number and would likely require management, in particular through hunting. Humans could also use dragons for transportation, increasing the likelihood that they would overlook their role in habitat destruction, thus improving the probability that the dragons could peacefully cohabit with people.

After completing this ecological assessment of the potential woes of global dragon infestation, we are confident that, although the situation may mean environmental calamity, it is rich with content for your potential use as a writer. We welcome additional inquiries about the ecological dimensions of a dragon-release event.

Most sincerely,
Dragon Den Modeling Agency

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