Khaleesi, Modeler of Dragons.

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Contents

1 Introduction

1.1 Overview

In this paper, we set out to analyze dragon behavior, habits, diet and additional interactions with Daenerys Targaryen's kingdom. After deriving a standard for dragon caloric and area needs, as well as general behavior of dragons, we develop models to explore how dragons affect the ecology and economy of Westeros.

We find the interaction between sheep and dragon population by accounting for the growth rate of sheep herds in various climates, as well as the caloric need for various sizes of dragons. From that, we discover the average lifespan of a dragon and the sustainability of our dragon population.

Beyond the ecological impact, we explore the economics that are involved with sustaining dragons. We calculate the cost of feeding the dragons and what can reduce the cost of owning a dragon. Additionally, we analyze the cost effectiveness of dragons in comparison to owning an army.

Finally, we discuss some real world applications of this analysis. These include modeling the reintroduction animals into the wild and the cost effectiveness of weapons.

1.2 Background

To fully understand dragon behavior and habits we must review the history of dragons and their role in Westeros. One of the most powerful societies in all of *Game of Thrones* lore is the Valyrian Freehold. The Valyrians were simple sheep herders until they discovered dragons living in volcanoes near their territories. They tamed the dragons and began to take over the surrounding area. Centered around the city of Valyria, the Freehold was undoubtedly the greatest civilization of its time, and at the height of its power covered over half the known world [1]. Their society continued to thrive until the Doom of Valyria, a massive volcanic explosion that killed the entire city of Valyria and their dragons [2].

The only Valyrian survivors were the Targaryens and their dragons who fled Valyria after hearing a prophecy of the Doom. They took up residence in the island of Dragonstone. Aegon Targaryen later conquered Westeros with only three dragons and a small army. He forged the iron throne with his biggest dragon, Balerion, and took up residence in King's Landing. After the conquest, the Targaryen dragons were kept in a large arena. Unable to roam freely, the dragons wasted away until they became extinct. The Targaryen dynasty later fell under the rule of the Mad King Aerys.

Seventeen years later, Daenerys Targaryen has hatched three dragons and she has her eyes set on the iron throne. We seek to answer how she could best sustain her dragon population and monitor their ecological and economic impact once she has conquered Westeros.

2 Energy and Caloric Need for Dragons

2.1 Mass and Wingspan of Known Dragons

Dragons are reptiles that are also magical creatures. Thus, to estimate their size and mass we must look to real world examples from the animal kingdom, especially reptiles, as well as *Game of Thrones* history and lore.

2.1.1 Estimating Dragon Wingspan

We chose to estimate the mass of known dragons in *Game of Thrones* lore. There are no exact measurements for wingspan, so we

based our estimations on a combination of quotes from the books and the TV show as well as official collector models.

Drogon *Game of Thrones* director, Matt Shakman, stated in an interview that Daenerys Targaryen's dragon, Drogon, is the size of a Boeing 747 in Season 7 [3]. Boeing 747s are approximately 230ft long with a 210ft wingspan. We therefore assumed that Drogon has a wingspan of 210ft which is 64m. We also noted that Drogon is six years old during the seventh season of *Game of Thrones*.

Viserion and Rhaegal Unlike Drogon, who was allowed to roam free throughout his lifetime, Viserion and Rhaegal were kept in captivity for a period lasting approximately three years. The growth rate of a dragon is slowed when kept in captivity, so Rhaegal and Viserion did not grow as large as Drogon. To determine their size in relation to Drogon, we refer to a set of collector models of Daenerys Targaryen's dragons [4]. In this set, Drogon had a wingspan of 38cm. In comparison, Viserion and Rhaegal had a wingspan of 15cm. Assuming these ratios are accurate, Viserion and Rhaegal have a wingspan around 25m.

Balerion In addition to Deanery's' dragons, we also included Balerion, the Black Dread, since this dragon also had data on size and age. Balerion lived to be 200 years old and is often cited as the biggest dragon who ever lived. Aegon Targaryen rode him during his conquest of Westeros. It was said that "his teeth were as long as swords, and his jaws were large enough to swallow an aurochs whole, or even one of the hairy mammoths that are said to roam the cold wastes beyond the Port of Ibben" [5].

To determine the approximate size of Balerion we assumed that his teeth were the size of swords. We then noted that a dragons mouth closely resembles that of an alligator. Similar to dragons, alligators have large teeth and long bodies. Alligators grow to a maximum length of 180in, and have 4in long teeth [6]. We assumed the average sword length is 36in, and that dragons have the same ratio of teeth to body length as alligators. Then Balerion's body would have been 135ft which is 41.1m long.

To estimate the wingspan of a dragon we chose to compare it to the albatross. They travel long distances, so they glide much like a dragon would. Wandering Albatrosses also make shallow dives when hunting, which is how the dragons have been shown to hunt in the *Game of Thrones* television series. The Albatross can be up to 1.35m in length and have a wingspan of 3.5m [7]. Therefore, our dragon would have an approximate wingspan of 107m if we assume it has the same ratio of length to wingspan.

2.1.2 Deriving Dragon Mass

We calculated the mass of our dragons using aspect ratio and loading capacity.

Aspect Ratio The aspect ratio (AR) of a wing is defined to be the square of the wingspan (s) divided by the wing area (A) [8].

$$AR = \frac{s^2}{A}$$

In general, high AR wings give slightly more lift and enable sustained, endurance flight, while low AR wings are best for swift manoeuvrability [9]. Dragons are known to travel long distances in *Game of Thrones*. Therefore, they would have a high aspect ratio. We then assumed that our dragons had the same AR as the wild albatross, which has an $AR = 12$. Using the formula above and

the wingspans calculated in section 2.1.1 we calculated the area of the dragons' wings.

Dragon	Wing Area (m^2)
Rhaegal and Viserion	52
Drogon	341
Balerion	954

Loading Capacity Wing loading capacity (LC) is defined as the body mass (M) in kilograms divided by the wing area in meters squared (A) [8].

$$LC = \frac{M}{A}$$

In general, wing loading for birds ranges from 1 to 20kg/m^2. The maximum possible wing load before the bird is too heavy for its wings and is unable to fly is about 25kg/m^2 [10]. Dragons have thick scales and dense bones, so they would be on the high end of loading capacity. Therefore, we assumed the loading capacity to be 25kg/m^2. We then used the equation above to calculate the mass of our dragons.

Dragon	Mass (kg)
Rhaegal and Viserion	1,300
Drogon	8,525
Balerion	23,850

2.2 Caloric Intake based on Dragon Mass

To determine how many calories a dragon would need to consume based on weight, a great starting point is the caloric intake of a tyrannosaurus rex. The caloric intake of a t-rex appears to cluster around 40,000 calories per day [11]. The average mass of a t-rex is 8160 kg [12]. Making use of Kleiber's Law [13], named after Max Kleiber for his biological work in the 1930s, we extrapolated the caloric intake for various sizes of dragons. Although the exponent, also known as the power law, has been an object of debate for many years [13], $\frac{3}{4}$ is adequate for reptiles. The equation follows.

$$MR \approx c * M^{3/4}$$

Here, MR is the metabolic rate of the reptile, M is the mass of the reptile and c is a derived constant. Using the data for a t-rex, we found the constant c by plugging in the values, $40000 \approx c * 8160^{3/4}$, we found that $c = 46.59$. Now that a value was found for c, the caloric intake was calculated based on dragon size. A table of calculated values can be found below:

Dragon	Mass (kg)	cal/day
10 kg Dragon	10	261
35 kg Dragon	35	669
Komodo Dragon	150	1,993
Rhaegal and Viserion	1,300	10,067
Drogon	8,525	41,255
Balerion	23,850	89,241

To verify Kleiber's Law, we also calculated the metabolic rate (calories/day) for the komodo dragons. Komodo dragons are a good means of estimation for dragons. Komodo dragons are carnivorous predators and eat large prey such as water buffalo, deer, carrion, and pigs [14]. They can eat up to 80% of their body weight in one sitting. Because komodo dragons are cold blooded, they can go multiple days between meals due to their slow metabolism. With this in mind, we can estimate a komodo dragon needs about 2000 calories per day.

Below is a plot that indicates how the metabolic rate of the dragon is related to the mass of the dragon.

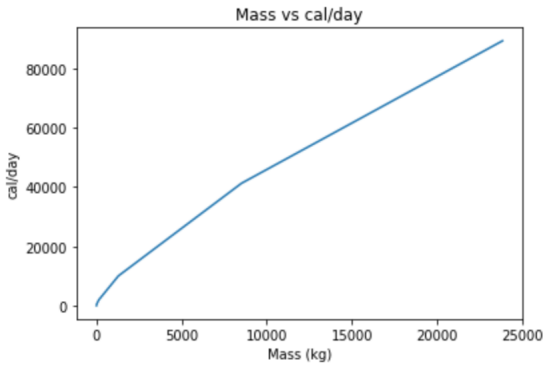


Figure 1: Metabolic rate given dragon mass

As lizards and other species increase in mass, they naturally require more energy. However, that does not necessarily mean that their metabolic rate will increase proportionately to their mass. Due to this fact, the slope of the dragon metabolic rate decreases as the mass increases.

3 Area Requirements for Dragons

3.1 Dragons in Captivity

Of Aegon Targaryen's three dragons used to conquer Westeros, Meraxes was killed in Dorne during Aegon's invasion, Balerion died in the peaceful reign of King Jaehaerys I, just under a hundred years after the Conquest, and Vhagar was killed in battle. The few surviving Targaryen dragons were kept in captivity and grew weak and sickly, with the last dragon (a creature not much bigger than a large dog) dying during the reign of Aegon III Targaryen, only 22 years after the death of Vhagar [5]. Clearly, dragon growth suffers in captivity. This lead to the downfall of the Targaryen household. Thus, we must allow our dragons to roam their given territory if we want to sustain the population.

3.2 Dragon Roaming Habits

Drogon When Drogon was allowed to roam free from the ages of three to six, he traversed the area around Meereen. He was spotted in many different locations spanning Westeros. In Season 5 of *Game of Thrones*, Drogon was seen in Valyria, which is approximately 1,000 miles from Meereen [15]. We also know he preyed on sheep near the great pyramid of Meereen and carried Daenerys to the Great Grass Sea, which is approximately 500 miles from Meereen [15]. Therefore, he was traveling in a radius that ranged from 500 to 1,000 miles.

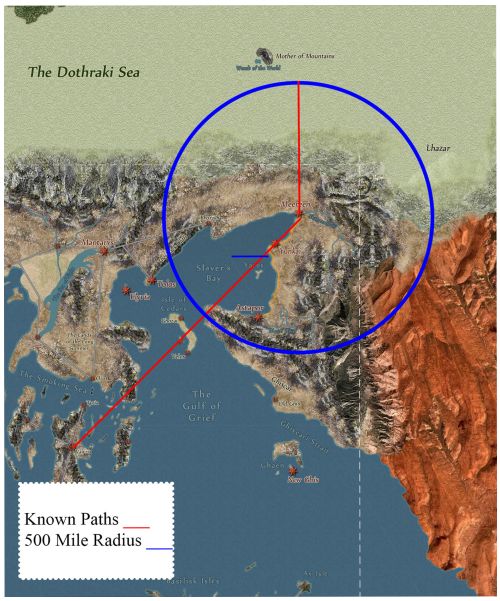


Figure 2: Drogon Roaming Habits

Syrax and Caraxes Syrax and Caraxes were two Targaryen dragons who were ridden by Rhaenyra Targaryen and Daemon Targaryen respectively. Rhaenyra and Daemon were known to race from King's Landing to the island of Dragonstone on their dragons daily [16]. King's Landing and the island of Dragonstone are 500 miles apart [15]. Therefore, a dragon can easily fly 1,000 miles in a day.

Figure 3: Syrax and Caraxes Roaming Habits

Assuming that a dragon will return home every night, and given the roaming habits of Drogon, Syrax, and Caraxes, our dragons will travel up to 500 miles away from home each day. Thus, the maximum area requirements for our dragons would be the area of a 500 mile radius circle, or 785,398 square miles.

3.3 Area Requirements for Feeding Dragons

3.3.1 Sheep Pastures

Dragons are large, carnivorous creatures with high caloric needs which was outlined in section 2. A dragon's favorite food is sheep, so a large area would be needed to maintain the sheep population. We have chosen to account for a rotational grazing system. Rotational grazing is a pasture system in which multiple pasture areas are used and livestock are moved to different pasture areas during the grazing season. Pastures need rest periods to recover from grazing and allow plants to regrow, so this will allow for a more sustainable sheep population [17].

The recommended amount of pasture for 1 sheep is 0.3 acres which is 0.0005 square miles [18]. For 100 sheep the needed space for grazing is 30 acres or 0.05 square miles. This allows for three 10 acre rotational pastures.

3.3.2 Farmers Needed

It takes about 2 hours of work per year to maintain one ewe and her offspring on farm pasture [19]. Thus, if we assume our farmers work 40 hours a week with some overtime over the course of a year, one farmer can maintain 1,000 adult sheep for our dragons.

4 Climate Conditions

4.1 Feeding a Dragon

Because dragons' favorite food is sheep, the community must be focused on providing enough sheep to keep the dragons happy. Sheep are able to be raised in many climates, although they tend to thrive more in temperate climates with enough rainfall to satisfy their food needs [20]. Arid climates, such as in India and Australia, temperate climates, such as the United States, and sub-arctic climates, such as Greenland have all been utilized for sheep farms.

4.1.1 Arctic Conditions

There is no way to grow food for sheep in the arctic climate north of the Wall, unlike the sheep farming locations in Greenland where grazing sheep is possible[21]. Attempts to graze sheep in arctic climates almost always fail. Alpine plants grow slowly and only for a short period in the summer. Sheep are usually the cause of upland erosion due to excessive grazing. Similar to how plants grow slowly, animals exhibit low reproduction rates in arctic environments and are at risk to environmental pressures [22]. Thus, other means

of feeding the dragons must be taken into account. There is a large seal population in the North, as well as mammoths and other arctic animals, so dragons could hunt these to sustain themselves [23]. However, this method is not as reliable as sheep farming. Thus, the arctic is not a sustainable place for a large dragon population, but a few lonesome dragons could survive.

4.1.2 Arid Conditions

Dorne is a large and arid region in the south of Westeros that could be utilized for sheep farming. Because dragon's sustain themselves primarily on sheep, the sheep in an arid environments must be carefully selected. Given the environment of Dorne and their exports (wine and exotic fruit), the need for wool is low, so we need to prioritize sheep with a high meat yield such as the Dorper variety [24][25]. Sheep in arid climates exhibit a lower annual herd growth rate than those in more humid and temperate climates, only around 1% per year [26]. Therefore, Dorne is an acceptable, but not ideal place for our dragon population.

4.1.3 Warm Temperate Conditions

Between The North (arctic conditions) and Dorne (arid conditions) lie a handful of lands that exhibit a temperate climate. Some of the lands include The Reach, Kingdom of the Rock, The Riverlands, The Vale, and Storm Kingdom [27].

In temperate environments, as well as arctic environments, a sheep's hairy coat is replaced almost fully with wool [20]. This means that not only can the dragons be fed with the sheep that are raised, but the community raising the sheep also has wool to trade. Additionally, sheep in semi-arid to sub-humid climates exhibit a higher annual herd growth rate, 1.5% and 3% respectively.

Climate Conditions	Annual Herd Growth Rate (%)
Arctic	0
Arid	1
Semi-arid	1.5
Sub-humid	3

4.2 Dragon Survival

4.2.1 Arctic Conditions

Dragons are reptiles, meaning they are cold blooded. This would be an issue in an arctic environment since the dragon would not have warm, outside temperatures to maintain body heat.

Many reptiles begin to slow their movements as the temperature begins to drop. Because dragons continue to function in cold weather, they must be stealing warmth from somewhere. Of course, dragons do produce their own fire, which may be a way to get around this issue.

There are two different ways a cold-blooded animal can control it's temperature, heliothermy or thigmothermy [28]. For larger animals, such as alligators, body temperature can also be maintained by thermal inertia [29]. Dragon temperature would probably be maintained by a combination of these methods.

Reptiles in Canada survive the winter through a combination of being able to tolerate their body freezing and "supercool" their body, which means letting the body get very cold while not freezing the fluids [30]. Dragons do not hibernate, so these methods would not be sustainable for a dragon. During the day, dragons could warm themselves by flying in the sun. In this way, their wings could help since they would have more surface area to draw heat in. The wings are also much thinner than the rest of their body, allowing the wings, and therefore the rest of the body, to heat up much quicker.

During the nights, the dragon would need somewhere protected to sleep. The far north in Westeros presumably has some kind of cave system since the show mentions the "cave dwellers" [31]. This is good news for dragons who can utilize these caves to help maintain their body temperature. This also corresponds to strategies reptiles use, such as burying themselves in the ground.

To use thermal inertia, dragons must be digesting their food and the metabolic thermal energy would carry over and continue to keep them warm. Therefore, dragons in an arctic environment would want to eat more than dragons in warmer climates. Since animals in these climates are rarer, while the dragons could survive, they would spend most of their time hunting for animals. The size of these dragons would be smaller than those of the south since many of their calories would go towards maintaining their body temperature. This smaller stature would help them fit into the caves (since there is no data on the cave system, we are assuming that there would be some a dragon could nest in).

4.2.2 Arid Conditions

Unlike arctic conditions, dragons would find comfort in arid conditions. As cold blooded animals that cannot control their own body temperature, they would find the warm weather comfortable. Dorne is the only location on Westeros that has a desert. Due to the warm and dry weather, the dragons, like lizards in a desert, would do well.

Arid conditions, though warm, tend to lack vegetation and fresh water. Since dragons do not appear to need to drink water, the lack of water does not present a problem. Additionally, the dragons are carnivorous so they do not need to concern themselves with the lack of greens. However, limited vegetation could lead to a limit on livestock. This issue is discussed above.

Another limitation of arid regions is that they typically get quite cold at night. Like lizards [32], the dragons may be able to bury themselves in the soft sand to stay warm at night.

4.2.3 Warm Temperate Conditions

Warm temperate conditions can be considered the ideal environment for dragons. Not only do they have an abundant supply of sheep due to the plentiful amount of vegetation, but the dragons also have plenty of warmth. During the long winters, the dragon can survive by similar means expressed in the arctic section above (flying in the sunlight to stay warm during the day). During the night, the dragons would likely be able to stay warm due to their internal fire since the cold is not nearly as extreme as it is in arctic conditions.

5 Ecological Impact

5.1 Population Models

Dragons will interact most heavily with the sheep population, so we modeled the population of dragons with the population of sheep. Previous models for sheep and wolf populations such as the NetLogo model [33] and predator prey models such as this stochastic model [34] that models sheep populations being preyed on by cougars have been used to model similar relationships. Our model is similar to Festa et al.'s, in that we use a stochastic model. Our model is made of several sub-models that approximate different factors that affect the dragons.

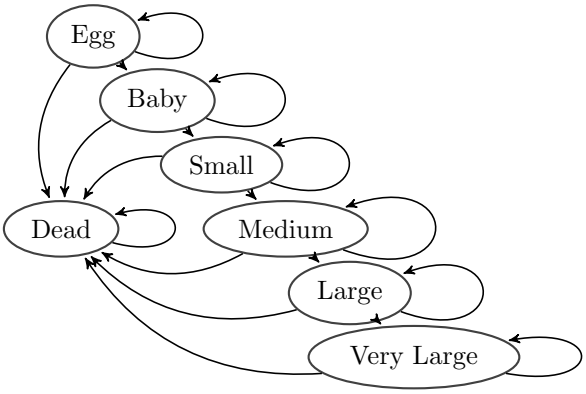
5.1.1 Dragon Model

Since the number of dragons alive at one time is a small number, we used a Monte Carlo simulation to determine the vitality of the dragon population. Each dragon has three

variables, size, whether it is wild or not, and the age.

Dragon Egg Laying Dragon "birth", or the increase of dragon eggs, is based on a fixed rate. This rate is multiplied by the number of dragons that are old enough to lay eggs. Since dragons are genderless [35], we do not keep track of whether a given dragon is male or female.

Dragon Growth Dragon growth involves moving up sizes. The different sizes of dragon are based on which animals the dragon is able to eat. In our model, dragons fall into six categories, baby, young, medium, large, and very large dragons. These categories determine how many calories each dragon in the simulation will need to survive. To simplify the modeling some, we assume that a dragon will eat only a part of a sheep if it is too small to eat a whole one. The probability of moving between these size groups depends on the age of the dragon and the food resources available. A graph of how the dragon life progresses is below.



The probability of transition is set up so the expected value of a random dragon size will be medium. This is the size of Rhaegal and Viserion.

Dragon Deaths Dragons often die in battle, so an expected lifespan is difficult to determine. The oldest dragon died at age 200 due to old age. This gives us an estimate of how long a dragon could live. However, death by old age does not mean this is the maximum time a dragon could live, so our model does allow dragons older than 200 years.

Lifespans as long as our dragons' is not unheard of in the natural world. Animals such as the Greenland Shark with a lifespan of around 270 years[36] and the Galapagos Tortoise with a lifespan of around 100 years[37] are examples of real world animals with exceptionally long lifespans. Since the longest surviving Galapagos Tortoise lived to 170 years, these are probably closest to the dragon in terms of lifespan.

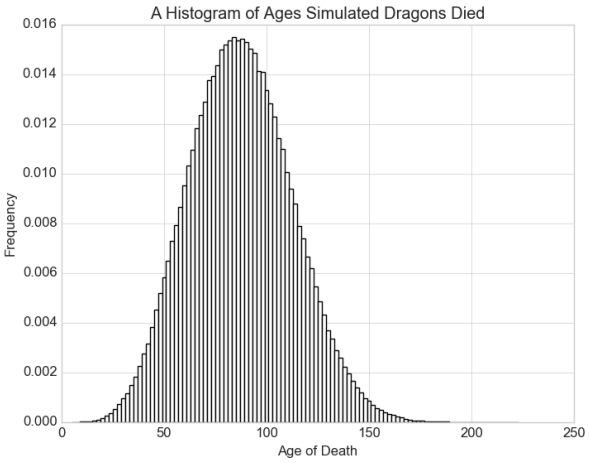


Figure 4: Lifespans of dragons given perfect conditions

Our model gives dragons an average lifespan of around 90 years, similar to the tortoise lifespan. The model gives a best case for the dragons, plenty of food, no war, and summertime conditions.

5.1.2 Sheep Population

Based on what season it is, the growth rate of the sheep population will be different. The growth rate for the summer was taken as the general growth rate for sheep in our world, between 1% and 3%. The growth rate for the

winter was given from a small negative rate, around -0.5%.

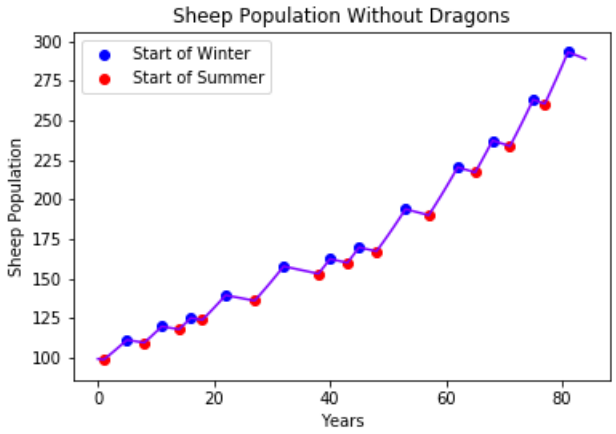
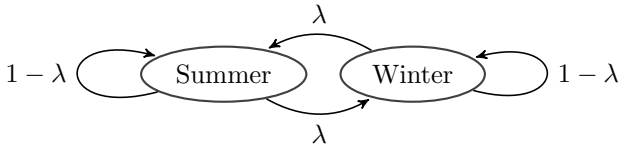


Figure 5: Sheep Population Growth

The figure above shows how the sheep population interacts with the environment. If there are no dragons involved, the sheep population will grow like an exponential function with periods of decline. The rate of growth during the summer was set higher than the rate of decline in the winter to ensure the sheep did not die out.

5.2 Weather Model

Weather in Westeros is different than that of our world. Seasons do not change for years and have an unpredictable rate of change. Seasons have lasted for up to 11 years at a time and can last for as short as 1 year. We simplified the seasons by grouping fall length with winter and spring length with summer, that way we could model only the switch between winter and summer.



We assume that summer and winter lengths have the same distribution, and that they are independent of one another. Independence is not quite accurate from what we know of the weather in the world, since longer summers often mean a longer winter is coming, but it is a good approximation. Due to the unpredictable nature, we assume these come from an exponential distribution. The mean was taken from the data helpfully compiled on a fan wiki [38]. The length of longer winters or summers are more often kept track of than the shorter ones, so the data with exact dates is fairly skewed. To mitigate this, we used the average length of winter and summer from Tyrion's birth, giving 7 summers and 7 winters with an average length of 2. This gives us a mean of 3.6 which seems reasonable for what we know of the world. Once we have this average, the probability of switching from winter to summer each year is an exponential with $\lambda = \frac{1}{3.6} = 0.278$.

Based on our model, the stationary distribution for this model would be $(\frac{1}{2}, \frac{1}{2})$, so on average, the weather will spend half of the time in summer and half in winter. This matches with what we know of the weather.

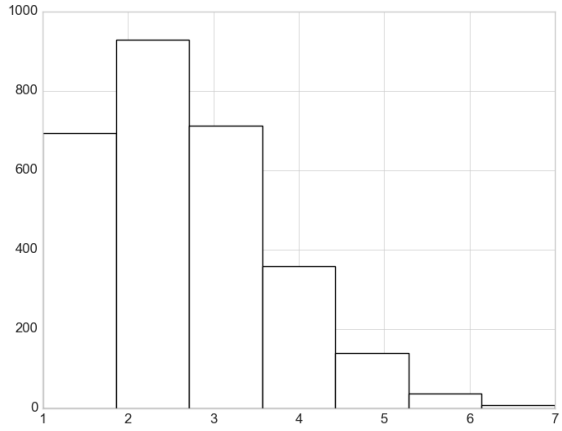


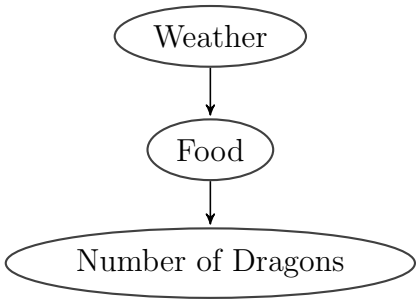
Figure 6: Number of years between season changes

The plot above was generated from running the season model for 10,000 years and

keeping track of how many years passed before the season changed. The number of years matches with what we know from the books, it seems most often the winters and summers last 1-2 years, but there have been extreme outliers of around 10 years.

5.3 Results

The complete model takes the current weather, the sheep, and the dragon population models. The sheep population is based on the current season and growth rate from location. Then the dragon population takes into account how many sheep are available.



Stability of the dragon population Dragons are notorious for low birth rates. However, if dragons lay too few eggs, their population will die out. The critical rate, beginning with three dragons is around 0.035. The dragons must lay at a rate equal to the number of dragons old enough to lay eggs multiplied by this coefficient. If they do not, it is much more probable that the population dies off.

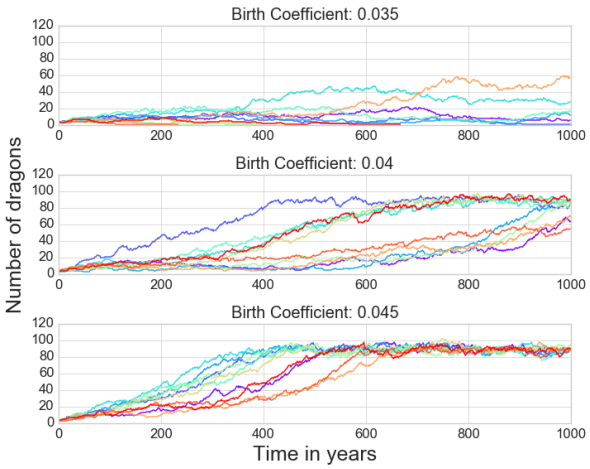


Figure 7: Comparisons of various coefficients for dragon births

We created this figure by holding the number of sheep to a large constant, so the amount of food was not an issue for the dragons. We also kept the probability of growth and death based solely on age.

When the sheep are added, the dragons must lay eggs at a higher rate, this rate was found to be about one egg every three to ten years. If the dragons do not lay this many eggs, they will die off, and if they lay more than this many, they will overeat the sheep. The birth rate from these eggs was given as a simple probability. While this is a simplification of the politics that go into a dragon birth, we believe this is accurate enough for the purpose of this model.

Dragon and Sheep Populations The sheep population in the complete model is based both on the number and size of dragons currently alive and the current season. To maintain a proper model, the sheep need to be replenished every once and a while. This would be like a tax on sheep from the feudal lords. The sheep from arid and temperate climates had decently stable populations, but any lower percentage of replacement would cause the dragons to decimate the sheep pop-

ulation in anywhere from a few hundred years to a few decades.

When the dragon and sheep populations begin interacting with one another, they tend to follow a predator prey type model. However, some key differences appear. In general, since our model only deals with the interactions between sheep and dragons, there are not enough dragons to control the sheep populations. This leads to the big spikes in the dragon population below. Since there are not enough dragons, the sheep population grows exponentially, allowing the dragon population to also expand rapidly. The peaks of these occur right before longer winters, which allow the dragon population to catch up to the sheep population. The sharp decrease in sheep population leads to the sharp decline of the dragon population. The plot below shows the dragon population (including unhatched eggs) for a thousand years.

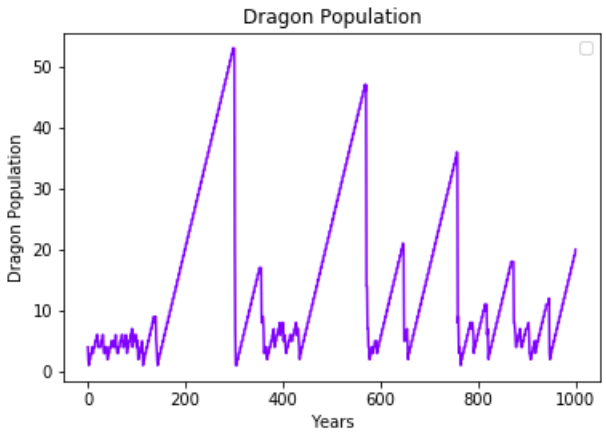


Figure 8: Dragon population with sheep and weather factors

Since the percentage increase in sheep changes depending on the climate, the model was run with each of these. In an arctic climate, the sheep died out and therefore, the dragons were unable to survive. In each of the other scenarios, however, the dragons did not eat enough of the sheep to strongly affect the population size.

6 Economic Impact of Dragons

6.1 Cost of Feeding Dragons

Feeding the dragons would be a costly and time consuming process. We assumed that transportation is not an issue, the dragon would be able to travel to where the food was kept and so transportation costs are not considered. The cost of keeping prisoners until execution is also not considered. We used the following variables to set up how much feeding the dragons would cost.

Given Variables

n = Number of dragons
$cnpd$ = Calories needed per dragon
h = Number of humans fed to dragons per month
cph = Calories per human
cps = Calories per sheep
pps = Price per sheep

We determined the values of each of these variables as follows.

Number of Dragons The number of dragons was left uncertain so cost per dragon could be calculated.

Calories Per Dragon The calories needed per dragon was calculated above and used here. The calculations presented here use the 10kg dragon, the 35kg dragon, Rhaegal and Viserion, Drogon, and Balerion.

Number of Executions by Dragon per Month The number of executions by

dragon depends on the crime rate in the land and how punishments are carried out. We are assuming that if someone is executed, instead of other means, all executions will be done by feeding to a dragon. Since Westeros society models society in the medieval era, we can estimate the number of executions that would happen in Westeros by the number of executions in medieval Europe. In Chester, England, detailed records were kept giving an average of 9 executions per year[39]. Since Chester is one county in England, we can count each of the 7 main houses as one county. While this may be a low estimate, since Chester is much smaller than these areas, Westeros also has the opportunity to join the Night's Watch instead of execution, an option many people would take. So on average, we estimate that 63 $(9 * 7)$ people would be executed each year, or about 5 people each month.

Calories Per Human The number of calories per human was based on an estimate of how many calories paleolithic humans could get from cannibalism [40]. While the end estimate of Cole assumes the human would not eat certain parts of the body, this does not apply to dragons. So we used the total calories in a human, also calculated in the paper, which came out to about 143,771 calories for an adult male.

Calories Per Sheep The calories per sheep was calculated using various online resources such as [41] and calorie counters for the sheep parts and then using Cole's analysis[40] of similar animals to cross reference about how many calories would be in the human inedible parts. Our estimation came out to about 40,000 calories.

Price Per Sheep An ewe in market can go for anywhere from \$60 - \$200 USD [42]. Most of this variation came from different locations in the US, and the variation in a location was around \$10 USD. So our model estimates sheep prices as \$100 USD.

Once these variables have been set, we created a simple linear model to show how the number of dragons changes the cost of keeping the dragons.

$$cals = n * cnpd$$
$$num\_sheep = \begin{cases} \frac{(cals - h*cph)}{cps}, & h * cph \leq cals, \\ 0, & else \end{cases}$$
$$cost = num\_sheep * pps$$

Looking at figure 9 below, we can see that to keep three Drogon-sized dragons would cost approximately \$5000 USD/month. In figure 9, we are holding the number of humans fed to the dragons constant at five humans per month.

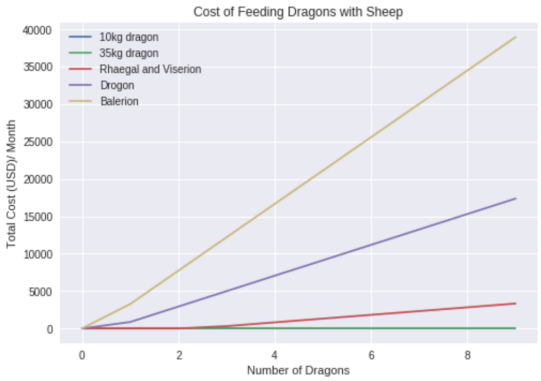


Figure 9: Cost of sheep as number of dragons increases

If the total number of calories needed by all dragons exceeds the total number of calories in the human sacrifices, then the economic cost will start to increase. Initially, the cost is zero because the humans fed to the dragons are costless. As the number of humans decreases to zero, the cost increases due to the new need to purchase sheep to feed the dragons.

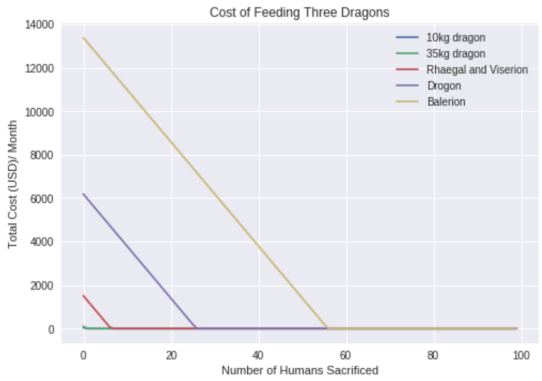


Figure 10: Cost per number of humans sacrificed to the dragons

In figure 10, we are holding the number of dragons constant at three. Here, if the total number of humans sacrificed is zero, then the cost to feed each dragon is high. The 10 kg dragon is not visible in either plot because the cost of keeping a creature so small is nearly insignificant compared to the larger dragons. As the size of the dragons increase, the number of human sacrifices increase in order to decrease the economic cost.

6.2 Dragons as Weapons

While dragons become quite costly if the number of human sacrifices is limited or if the number of dragons increase or if the size increases, the cost is mitigated when the military benefits from the dragons outweigh the cost.

Context Two large battles that involved conquering Westeros in *Game of Thrones* were Aegon's Conquest, where Aegon Targaryen conquered most of Westeros as he united six of the seven kingdoms, and Robert's Rebellion, which was a rebellion against House Targaryen.

In Aegon's Conquest, Aegon, the Targaryen fleet, three dragons (Balerion, Vhagar, Meraxes) and a number of royal houses engaged in battled with an army of approximately 50,000 soldiers. Aegon's army can be approximated to 5,000 soldiers excluding dragons. [43]

In Robert's Rebellion, the rebels and the Targaryen's both had armies that were made up of 50,000 soldiers.

Dragon Versus Army If we assume that a human needs approximately a 3 foot radius for battle and every single dragon's fireblow (regardless of size) has approximately a 15 foot radius [3] (also assuming that they blow fire directly down at the ground and all of Westeros is flat), then we can estimate the economic benefit of keeping a dragon.

Figure 11: Drogon's Fire Radius

Let's assume that an army is made up of 50,000 people. This means that for a 3 foot radius per person, the whole army takes up about $1,413,717 ft^2 \approx 0.05 mi^2$. Then, knowing that the radius of a dragon's breath is $225\pi ft^2$ then we find that one dragon blow at an army (assuming the army doesn't scatter or spread more than the area estimated above) will kill approximately 25 people. For a 50,000 soldier army, this would mean that a

dragon would need to blow fire 2000 times to defeat the opposing army of 50,000 soldiers.

Dragon Cost Benefit Now, let's assume that each soldier must be paid $480 USD per day [44] (assuming pay for medieval squires) and that there is only one battle per year. For an army of 50,000 soldiers, the total pay for that one battle would be $24,000,000 USD.

Note that 25 people is equivalent to 3,569,275 calories. If we assume that the human meat from battle will expire and be inedible for the dragons after 10 days then the dragon cost is only reduced by a small amount. If the dragons are the same size as Balerion, then one fireblow can feed four dragons for 10 days. If the dragons are the size of Drogon, then we can feed eight dragons for 10 days. If the dragons are the same size as Rhaegal and Viserion, then we can feed 354 dragons for 10 days.

Let's assume we are only looking at purchasing one dragon for our army that goes to battle once a year. If we are able to feed the dragon for 10 days from the kill from battle, then the final piece to determine is how many sheep we need to purchase in order to feed the dragon for the remaining 355 days.

Given Variables

$dc =$ Calories a dragon needs for 355 days
$hsy = 5$ human sacrifices per month
$hc =$ Calories in a human: 143,771
$sc =$ Calories in a sheep: 40,000
$ps =$ Price per sheep: 100
$nsd =$ Number of sheep needed for 355 days
$scd =$ Sheep cost for 355 days

$$nsd = \frac{dc - (\frac{hsy}{365} * 355 * hc)}{sc}$$
$$scd = ceil(nsd) * ps$$

From this, we can verify the data presented in 10 that a single 10kg dragon, a single 35kg dragon and one dragon the size of Rhaegal and Viserion can all be fed strictly with human sacrifices and cost nothing. Drogon must be fed with approximately 157 sheep and Balerion must be fed about 583 sheep in addition to the battle human deaths and human sacrifices.

Still, we find that purchasing 583 sheep is only $58,300 USD/year as opposed to the $24,000,000 USD/year. Assuming that during battle, a dragon can kill 25 people when a human could kill one in the same amount of time, the army would be better off purchasing a dragon that is the size of Balerion than sending an army of 50,000 soldiers into battle.

Given that the average soldier during medieval times could kill 8 people per battle [45] and that a dragon can kill 25 people in one breath, then the dragon kill estimate is incredibly conservative. If a dragon needs to breath the same amount a human needs to breath and a human breaths 12-20 times a minute [46] then the dragon could do significantly more damage. Assuming that the dragon breaths fire every five breaths during battle then the dragon can obliterate the whole army after approximately 8 hours. If each soldier killed 8 people per day, then the battle would last significantly longer.

If the soldier count remains at 50,000 soldiers, then the maximum number of dragons that can be purchased for the same price is about 411 dragons.

Excluding Monthly Sacrifice In the equation in the previous section, part of the calculation for number of sheep to feed a dragon for 355 days (-10 days for food gained from battle) included a subtracted value for human sacrifices. If we choose to not execute humans by dragon, then the total cost

over the 365 days increases by an insignificant amount which does not make the purchase of a dragon any less worth it. For example, a dragon of Drogon's size would cost $15,700 when including monthly human sacrifices and $36,614 when excluding.

Dragon versus Dragon Now, the situation where each army has at least one dragon challenges the previous assumptions. The most significant ways a dragon can die are by another dragon or with a Dragonbinder which is a special magical object that allows the user to gain control over dragons. Setting Dragonbinders aside (as they had not appeared on the show prior to season 7)[47], the other way to kill another dragon is with another dragon. Given our assumption above that regardless of the dragon size, the radius of its fire is the same, the dragons will be fairly evenly matched. Their differentiating factors would be the size of their claws but for a simple model, it's reasonable to set that aside as well. So, if two armies have one dragon each, they are evenly matched and the only way one would be able to over come the other is with another dragon.

Given the radius of destruction that the dragon fire has, it's reasonable to assume that each side would want to decrease the use of dragons in warfare. Though the more dragons a side has the stronger it is, those dragons could lead to irreparable damage such as forest fires and field fires. A dragon becomes a valuable asset to have but not necessarily to use. This means that the optimal number of dragons to have is either as many as possible or have none at all in the whole world.

Having zero dragons in Westeros would lead to better matched battles. Introducing a single dragon in to the equation makes every battle incredibly unfair and the battle may as well not be fought. As soon as there is more than one dragon, the side with the most dragons is the most powerful.

6.3 Wild Dragons

Another issue that will arise with the spread of dragons is wild dragons. Historically in Westeros, wild dragons would come and steal sheep. If the population of wild dragons got out of control, there would need to be a culling of the dragon population. The task of killing a dragon is incredibly dangerous, so the wild dragons would have to be very costly before measures would be taken to cull the wild population.

Using the same model used to calculate the cost of buying sheep for dragons, we found that a single dragon the size of Drogon, unable to eat prisoners, will need 24 sheep a month. This amounts to a loss of about $2,350 USD per month.

Since dragons are so difficult to kill, we could guess that it would be as difficult as winning the gold medal in the Olympic games. The cash prize in the United States for winning the gold medal is $37,500[48].

Putting this bounty on the dragon's head will pay back for itself in a little over 15 months, ignoring the repercussions of the herd diminishing at such a rate.

According to the books, a dragon, Sheepstealer [49], was tamed by giving a sheep to it every day. If this method were used, the community would need to decide whether they can support a dragon and whether the defense capabilities would outweigh the resources they would need to give up to help maintain the dragon.

7 Real Life Application

While modeling dragons is fun, dragons are mythical animals and modeling their interactions will not directly apply to the modern

world. However, principles from this analysis can be applied to various scenarios.

7.1 Reintroduction of Endangered Animals to the Wild

In *Game of Thrones* season one, the dragons are considered to be extinct with the only remains being a few petrified dragon eggs which are considered useful only as decorations [35]. Since dragons were extinct for approximately a century, society had adapted to a life without them. Our analysis begins when dragons are reintroduced to Westeros.

Reintroduction is an incredibly delicate act and the act has the potential of effecting the ecology as well as the economy. Many conservationist are wary of reintroduction of wild species due to the fact that a new species could cause native species counts to decline [50]. Even though dragons are native to Westeros, the fact that wild, untamed dragons might steal farmers sheep that could have gone towards feeding domesticated dragons or towards feeding the people could cause economic problems. Since sheep are considered assets for the farmers, the loss of sheep could lead to less trade and purchasing power for consumers (wealth effect [51]).

Our model mentions what can be done about rogue animals (a bounty) but one study found that killing or trapping wild wolves that attack livestock or are effecting a human neighborhood might cause them to migrate to a new neighborhood. Thus, the wolf problem persists despite killing part of the pack. Arya Stark describes this dilemma in Season 7 of *Game of Thrones* after she kills Walder Frey, "leave one wolf alive and the sheep are never safe".

Similar to our dragons, wolves are not always an unwelcome presence. For example, wolves were reintroduced to Yellowstone National Park in 1955. Yellowstone wants their wolf population to succeed. Instead of killing problematic wolves, the park rangers haze them, which includes yelling, clapping hands, honking the horn, paint balls, bean bags, and cracker shells [52]. Our dragon and sheep population model could be expanded to represent wolves and their various forms of play including but not limited to bison, elk, and deer. This could help park rangers predict the size of the wolf population in relation to weather and herd growth rates.

7.2 Use of Weapons as Opposed to Soldiers

Given the analysis in section 6.2, one can draw parallels between the possession of dragons and the possession of nuclear weapons. The dragons in Westeros exhibit significantly higher power than an army that an army becomes nearly irrelevant. Similarly, in our modern world, there are various nations that possess nuclear weapons. Due to the massive destructive power of nuclear weapons, the nations that have access to these weapons have signed a treaty [53] in which they agreed to promote peaceful uses of nuclear energy as opposed to the weaponization of it. The reason for maintaining armies instead of replacing them with dragons follows a similar thought process.

Not getting into thermodynamics, if the radius of a 1 megaton nuclear blast is approximately 1.5 kilometers with a radius for 50% chance of death of 8 kilometers [54] and a dragon's fire is about 15 feet or 0.0046 kilometers and we assume that the two are proportional, then we can estimate that one dragon's breath can do significantly more damage than estimated above. So, the dragon's breath has a radius for 50% chance of death about 0.0245 kilometers which is about 80 feet.

So, given the complete obliteration that

would occur if either side used nuclear weapons, nations choose not to use them as a sign of peace but keep them due to the illusion of power they give. The *Game of Thrones* television series and the novels depict the battles as incredibly violent and the dragons do less damage than our calculations find. A more realistic behavior would be to intimidate opposing armies by having them know you have dragons that could be used.

The effectiveness of letting an opposing nation know that you are in possession of nuclear weapons has been observed in North Korea. The US has been more hesitant to invade North Korea due to their nuclear weapons. Countries that own these weapons have the ability to deter countries that would want to invade. [55] If this logic transferred over to Westeros, then armies should be hesitant to invade other lands if those lands have dragons.

7.3 Modeling Dinosaurs and other Extinct Creatures

In section 2, the size and mass calculation for dragons was based off of various notes from the director, quotes from the novels as well as comparisons to alligators, albatross, and 747s. We then referenced a paper that determined the caloric need of a tyrannosaurus rex and komodo dragons and proceeded to extrapolate what the caloric intake of various sized dragons would be. Based on mass and caloric intake, we were able to model how many sheep the economy would need to provide to sustain different sized dragons as well as how much it would cost. This model included monthly human sacrifices and humans killed in battle.

To transfer parts of this model to dinosaurs and other extinct creatures, we need to exclude human sacrifices and humans killed in battle. Since dragons are fairly domesticated in our model, modeling extinct wild animals would change aspects of our model. However, knowing the mass of, say, a pterodactyl and knowing the frequency at which they consumed fish and other creatures [56] would allow for the calculation of their metabolism's rate. However, unlike dragons, pterodactyl were warm blooded to the constant used in Kleiber's Law would need to be increased to account for a faster mammalian metabolism.

8 Conclusion and Future Work

Dragons have a big impact on the world of Westeros. We start by modeling this impact by modeling the dragons themselves. Dragon's caloric needs are calculated based on extrapolating from real world animals and various data we have about the dragons in the show. Once this is completed, we also find the area necessary for a dragon to remain happy and healthy. Climate conditions are a concern for the dragon's well being and ability to find food, so these are taken into account in our model as well. Once these variables have been honed, we use them to model the ecological and economic impact dragons have on Westeros. The ecological impact was modeled using a stochastic algorithm. The algorithm modeled the weather, sheep population, and dragon population and how these interact with each other. The economic impact was also modeled by determining how much it would cost to feed a dragon. We found it is much more economical to owning an army. However, if more dragons are fighting on different sizes, it is better to have the dragons, but not use them.

Future work from this could include a better analysis of the model. While the dragon and sheep populations appear to be spiking

chaotically, a full analysis of how these interact would be useful. A deterministic weather model would also be useful, so the direct impact of long summers and winters could be measured. Dragons have many other impacts on the ecology and economy that were not considered here. For instance, wild fires can cause massive shifts in the ecology and economy, so modeling how the dragon fire would spread and how a dragon raises the chance of a wild fire would be a worthwhile consideration. Dragons could also be used to transport goods from one location to another. This would bring more prosperity to Westeros as trade would become cheaper and quicker. This would help raise the economy of the country.

Letter: Ecology in *A Song of Ice and Fire*

Dear George R. R. Martin,

Upon performing an in depth study of the dragons presented in your novel *Game of Thrones: A Song of Ice and Fire*, we regret to inform you that we have discovered some potential ecological and economic problems in the Westeros society as the dragon population increases. Dragons can have significant economic and ecological impact on the areas they choose to live in. To maintain a sense of realism, aspects of the dragons' interactions such as how economical it is to have a dragon instead of an army, how the society of Westeros would keep the dragons fed, and how the dragon would survive in different climates need to be checked.

Admittedly, we made many assumptions to simplify the model. For one, we assumed that dragons, regardless of size, breath the same size radius of fire as soon as they are battle size. This assumption allowed us to compare the effectiveness of commanding an army of approximately 50,000 men to owning one dragon. We based this assumption off of the radius of fire breath for Drogon that was released by the director, 15ft. Assuming this measurement is accurate, we find that having one dragon is more valuable than an entire army. Not only is it better to have a dragon over an army, it saves soldiers' lives by not sending them into battle and is more cost effective for the army over all.

From an ecological stand point, the most significant interaction we accounted for was between dragons and sheep. To model their interaction, we took into account how much space a dragon needs to roam, how much food is available (i.e. sheep), and caloric needs of dragons based on their weight. Our model has an average dragon lifespan at around 90 years, with the oldest ones living around 200 years.

The sheep population in our model is based off of the number and size of dragons as well as the season. The sheep growth rate changes whether the season is summer or winter, the sheep population will decline in the winter months where food is scarce. The sheep growth rate is also dependent on climate, the sheep population will grow fastest in temperate climates and and slower in arid ones. The dragons in this model are dependent on how many sheep there are to sustain them. The results from this give us a predator-prey model where the sheep population will increase causing the dragon population to increase until the dragons eat too many sheep. At this point, the sheep population crashes, causing the dragon population to suffer a steep decline. A difference in this model to normal predator-prey models is how the seasons affect when the sharp decreases occur. When winter hits, if the sheep and dragon populations are close to the tipping point, they will suffer the decline. From our simulations this could be as drastic as decreasing from around 30 dragons and dragon eggs to around 5. Sometimes, short summers are not enough to pull the population out of this decline. For the dragons to be able to survive the decline in population, they must lay on average, an egg every one to ten years. Note that this is based on our approximation of how often a dragon is born, with a lower birth rate, the dragons could lay eggs at a lower rate as well. Weather considerations should be taken into account when determining how many dragons the world could sustain.

We found that it takes one farmer working 40 hours a week to take care of 1,000 sheep. A dragon of Drogon's size will consume approximately 376 sheep a year. This suggests it would not take very many more sheep than are currently in the world to keep Khaleesi's

dragons well fed.

When taking the climate of different regions into account, we considered the ability to maintain sheep and how a dragon would handle the different temperatures in arctic, arid, and temperate climates. Overall, in arctic conditions, dragons will have a hard time on all accounts. In temperate conditions and arid conditions, the dragon will be more comfortable. Due to temperature and it's ability to produce sheep, temperate climates are the ideal location for dragons.

If the dragons are cold blooded, they should find it difficult to retain body heat in frigid temperatures. If a dragon is trying to survive beyond the wall, it would need to have strategies to maintain it's body heat. One solution to this issue is that the dragons could stay warm by flying in the sun during the day, and stay warm in the caves of the far North at night. Since dragons breath fire, they could keep warm that way, however, they would have to sustain the fire for long periods of time in order to reheat themselves. This would require many more calories than the dragons in the south needed to survive. However, it is virtually impossible to raise sheep in the arctic, so the dragons would not have a reliable food source. Some dragons could solve this by hunting other prey, but there must be a much smaller community of dragons living in the arctic. Additionally, dragons in the arctic would most likely be smaller than those living in warmer climates, since their energy would be spent maintaining body heat instead of growing.

Moving from arctic to arid conditions, the dragons would be significantly happier. However, they would still face problems when it came to sleeping at night. Since deserts have a tendency of becoming cold at night, the dragons must find a place to stay warm. Many desert lizards bury themselves in the sand to stay warm at night so, in order to maintain realistic ecological reasoning the dragons should follow suit. Sheep survive reasonably well in arid conditions given a proper amount of food, so the dragons will not lack resources.

Like Goldilocks and the three bears, arid and arctic are not quite perfect but temperate weather is just right. The dragons body temperature will remain regulated in a temperate climate and the sheep are plentiful.

Overall, if your goal for future novels is to create a more realistic world for these mythical creatures, the first place to start would be to look into ecology and the climate. The addition of ecological models would maintain realism.

Regards,
Your hardworking research team

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