Models for Sustainable Population Growth on Mars

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1 Problem Statement and Approach

In the United States, the National Aeronautics and Space Administration (NASA) has announced its plan to send humans to Mars during the 2030s. This ambitious goal requires a variety of studies be conducted to effectively plan the endeavor. General habitation, food production, resource extraction, communication, spacecraft, and many other areas must be studied to determine their optimal configuration.

For our second project, we propose a simulation of population growth dynamics on Mars, with the goal of determining an optimal strategy for sustainable population growth. Population growth models have been extensively studied in the literature [5], [4], [17], [3], [9] but generally only in the context of our own planet.

Often, natural populations without resource limitations exhibit exponential growth [2]. However, this type of rapid growth will likely be unsustainable under the extreme resource constraints of Mars. By considering several proposed habitation models for Mars, and modeling the effects of uncertainty, we hope to better understand the viability of these approaches, and by that develop recommendations for sustainable growth.

2 Related Work

2.1 Population Growth Models

Moore [21] introduces five models of human colonization. The study focuses around expansion of colonies by modeling migration patterns of the population as well as mortality and fertility rates. The five models of colonization mentioned are the matrix model, beachhead model, string of pearls, outpost model and the pulse model. The paper concludes that regardless of population size, low fertility rates and/or high mortality rates will cause colonization to fail.

There has been previous literature on modeling population growth with limited resources. The most popular model used for population growth is the matrix model. Miller et al [19] use a Leslie matrix model to estimate the annual increase of a gray wolf population. This model takes inputs of survival and fertility rates and is modified for an environment with limited resources. A simple density-dependent matrix model is used based on a discrete time scalar logistic equation with a defined carrying capacity factor. The estimates for the projection matrix, including survival rates, fertility rates, litter size, and carrying capacity, were taken from field studies of real populations. Aikio & Pakkasmaa present additional characteristics to model population growth by linking growth and reproduction rates with an individual's biomass and the number of individuals they interact with [1]. Clark & Innis uses a model that integrates energy and protein relationships for jack rabbit population growth where the limited resource is food [6]. Food intake is controlled by energy balance and gut fill while foraging selection is used to balance nutrients. The growth and reproduction rates have energy and protein requirements while mortality rates are influenced by predation from coyotes and natural causes. Peterson et al [23] also introduces a matrix model structure around population dynamics of trees in a forest and mentions the ease of computer simulation as a factor behind using the matrix model structure. The forest matrix model predicts population dynamics using vectors of live trees as well as growth and recruitment matrices.

2.2 Food Production

A stochastic model of population growth during the Neolithic transition focused on foragers and farmers is presented by Fedotov [10]. A two-population model is used in which foragers and farmers are modeled separately but maintain a relationship through total population density. Crop production is also modeled by a formula based on soil nutrients and production rate. The density of soil nutrients is modeled as a partial differential equation, taking into account population size and crop production per unit of time. The study discusses the change in food supply as population density increases and farm land degrades; however, there are underlying assumptions that do likely not apply to the case of colonizing Mars (such as erosion and flooding). Despite the model's objectives being different from our own, the modeling of crop production and soil nutrients appears transferrable to our application with the proper tailoring.

Fedotov's study [10] suggests the use of phosphorus as the predominant indicator of nutrients in soil. As such, the relationship of phosphorus excreted by human subjects as a function of protein intake [18] can be applied to our problem to quantify the ability to reconstitute soil for farming by using human excrement.

A study by the Food and Agriculture Organization of the United Nations

(FAO) [12] further adds value to our study by providing the amount of animal and plant-based protein consumed by individuals from a multitude of contries. Given our study's focus on NASA, figures from the United States can be gleaned. Other information from the FAO [11] provides figures for crop efficiency, quantifying edible energy and protein per hectare of farming land for a selection of key crops.

Finally, a study related to hydroponics [7] presents a final useful component to the modeling of food our study, where the effectiveness of hydroponic gardening is compared to that of conventional crop growing techniques by analyzing one of the crops found in [11]. At the conclusion of the study, a multiplier is noted that could be used to approximate the amount of food the Mars colony can grow using hydroponics when compared to the amount grown by conventional means. In this light, it may be attractive for the Mars colony to use hydroponics in lieu of conventional farming techniques.

2.3 Mars-Specific Habitation Models

2.3.1 Oxygen Generation

The distance from Earth to Mars varies between roughly 58 million and 400 million km. Because of the great distance, resupply capbilities for human missions to Mars are virtually nonexistent. Due to this challenge, innovative approaches must be taken to regenerate necessary resources in-situ. To this end, the Mars Design Reference Architecture 5.0 [8] proposes the use of an "In-Situ Resource Utilization System" (ISRU) that converts Mars atmosphere into oxygen for both propellant and life support purposes. The plant operates by using electrolyzers that convert carbon dioxide into oxygen and carbon monoxide, which is then vented. A hydrogen feedstock is brought from Earth and reacted with Mars-produced oxygen to generate water. Furthermore, carbon dioxide, nitrogen, and argon that are extracted from the atmosphere of Mars can be employed as a buffer gas for crew breathing.

2.3.2 Power Generation

The lack of known resources on Mars that can be mined for power generation requires either a solar-based power source or a power source transported from Earth [14]. As noted, Mars is roughly 50% farther from the Sun on average relative to the Earth, so only around half of the solar radiation that Earth experiences actually reaches Mars. Thus, the Design Reference Architecture [8] proposes the use of a nuclear fission-based reactor. Of the power sources which can be transported from Earth, a nuclear power source is the only known option that concentrates sufficient energy in a reasonable mass and volume [14]. The reactor operates at a low temperature, allowing stainless steel (which is compatible with Mars' atmosphere) to be used for reactor components. The ISRU plant mentioned previously is a predominant consumer of power (consuming 25 kWe when operating continuously).

2.3.3 Space Agriculture and Waste Processing

The daily resource requirements of humans have been studied through computer simulation [25]. Simulations indicate that a human requires (per day) 855g of food inputs, 4577g of drinking/food preparation water, 128g of water in food, 18,000g of wash/flush water, and 804g of oxygen for food metabolism. In terms of outputs per day, they are separated into three categories: water, solids, and carbon dioxide. Humans produce 3025g of water in urine and feces, 406g of metabolic water (vapor), 1680g of perspiration water (vapor), and 18,000g of wash/flush water. 161g of solids in the form of feces, urine, and sweat solids are produced. 1092g of carbon dioxide from food metabolization is produced. Over the course of a year, this means that the average human is consuming roughly "three times his body weight in food, four times his weight in oxygen, and eight times his weight in drinking water." [20]. Thus, bioregenerative systems are essential to sustainable long-term habitation on Mars.

To enable space agriculture, hyper-thermophilic aerobic composting bacteria have been studied specifically in the context of habitation on Mars [15]. This technology can be implemented as a subsystem that oxidizes inedible biomass/wastes, converting them to fertilizer. High quality compost is an important part of a regenerative food production system, but as noted, must be implemented carefully to avoid the spread of pathogenic bacteria. A "marsh-based waste processing system" [22] has also been studied which exploits the natural ability of aquatic plant/ microbial associations to perform processing of waste. These systems metabolize, or concentrate, pollutants while generating useful biomass growth. Furthermore, aquatic plants can be used as purified water sources by condensing moisture evapotranspired from plant leaves.

In another study [16], a menu for a sustainable human diet on Mars was developed, concluding that a combination of rice, soybeans, sweet potatoes, green-yellow vegetables, silkworm pupa, and loach would fulfill human nutritional requirements.

3 Simulation Description

In population dynamics, birth and death rates are often density-dependent [13], in that the birth rate eventually decreases as population size increases, and the death rate also begins to increase with population size due to resource unavailability, environmental deterioration, or both. The *logistic growth model* is often used for modeling population growth that does not grow without bound. In continuous time, the logistic growth equation takes the form:

$$\frac{dN}{dt} = r\left(1 - \frac{N}{K}\right)N \tag{1}$$

where r is the intrinsic growth rate, which can be understood as the birth rate minus the death rate, and K is the carrying capacity, or the maximum population a species can sustain indefinitely. For purposes of our simulation, we introduce stochasticity to this deterministic framework through the following procedure previously noted in [26].

We intend to model humans as consumer entities, and several types of resources such as food, water, and sanitation availability as resource entities. We intend to take a stochastic, discrete-time approach. As David Quammen notes [24], there are four sources of uncertainty to which a population may be subject: demographic, environmental, natural catastrophes, and genetic. We will attempt to model several of these to provide the greatest realism possible.

3.1 Inputs

3.2 Outputs

3.3 Parameters

3.4 Content

3.5 Assumptions & Simplifications

4 Simulation Architecture

5 Progress To Date

From a programming perspective, we plan to use the Python programming language, which is object-oriented, dynamically typed, and interpreted, making it an excellent choice for developing our simulation in an iterative manner.

6 Task Plan

Going forward, tasks for for our team will be divided as follows:

- Chris will be focusing on developing
- Allen will focus on
- Matt's focus is

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