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Island archaeology provides ecological and behavioral analogs for off-planet exploration and colonization

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ABSTRACT

Human exploration and colonization of the solar system will involve the physical presence of humans, their materials, and accompanying translocated species in novel environments. This process will entail a series of scenarios (from short-term, behavioral adjustments to longer-term, ecological impacts) that are impossible to recreate faithfully; either because of their intrinsic infeasibility, or because of ethical constraints associated with human test subjects. Necessarily, we must instead rely on analogs or models. We argue that the best model for solar system colonization is that provided by island settlement by humans during the Holocene. Despite the behavioral and ecodynamic outcomes of the human colonization of islands being relatively well-understood, there has been no systematic attempt to utilize this information to inform space exploration. The outcomes of such an attempt are likely to provide a more concrete understanding of future off-planet human activity and the associated implications.

1. Introduction

Human exploration of, and expansion across, the solar system will involve the physical presence of humans (and potentially artificial intelligences), their materials, and accompanying translocated biota including microbiomes in novel planetary and lunar environments (NASA 2022). This expansion will have broad impacts of several types, ranging from impacts on the human body and social structures to those on off-Earth physical systems. Indeed, some scholars argue that these impacts are already being felt: Holcomb et al. (2024) suggest that anthropogenic geomorphic effects on Earth's moon constitute a 'lunar Anthropocene'.

The likely nature and extent of these impacts has generated a broad scholarship. Major preoccupations include the effects of space exploration and colonization on established political and economic structures, often viewed through a lens of sustainability studies (e.g., Broniatowski & Weigel, 2008; Iliopoulos & Esteban, 2020; Rementeria, 2023; Shaghaghi & Antonakopoulos, 2012; Vedda, 2008), as well as the efficacy of off-Earth human existence over long time scales (Miraux et al., 2022; Sawik, 2023; Walker and Granjou, 2017). In addition, there has been substantial consideration of the intrinsic value of human exploration of space, including societal impacts over the very long term (Gunderson et al., 2021; Torres, 2018; Ćirković, 2019). Biological risks of space exploration have also been addressed (Kovic, 2021; Szocik et al., 2018; Szocik et al., 2021).

Much of this literature is either oriented around a technological theoretical framework (the technological problems intrinsic to space exploration and their solutions), or around a normative theoretical framework (humans should act to avoid or promote certain

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circumstances). Here, we pose a different problem. The arrival of humans and their materials in previously human-free contexts will drive a series of scenarios that are *currently impossible to model* via direct experiment, observation, and inference. We argue that the archaeological and palaeoenvironmental record of Earth's islands—most notably those demonstrably free of the genus *Homo* until the Holocene—provide excellent yet under-utilized analogs for understanding the human colonization of near space. We first outline key aspects of knowledge-limitation in off-Earth exploration and colonization, and then show how rigorous meta-study of ecological and behavioral analogs in terrestrial island colonization could mitigate these limitations.

2. Knowledge-limitation in off-Earth exploration and colonization

Humans have already launched remote probes through and beyond our solar system. Over the short-term, physical human presence on Mars (and a return to Earth's moon) seems increasingly likely (Giachino et al., 2023; Shaghaghi & Antonakopoulos, 2012; Szocik et al., 2018); over the medium- to long-term, human presence on the rocky and icy moons of the gas giants is also possible. This expansion will involve a series of scenarios.

2.1. Behavioral and demographic scenarios

To reach any of the inner planets, the Main Asteroid Belt, or the moons of the gas giants, humans will have to travel for months or years. This presents a range of physiological and psychological-behavioral challenges (Blackwell Landon et al., 2023; Kovic, 2021). During time spent away from Earth, humans will be subject to a comparatively unusual situation; they will be largely free of immediate institutional oversight and censure. That is, if their behavior is considered socially transgressive, or more generally deviates from the normative expectations of the wider institution responsible for the mission, they will to an extent be beyond the reach of an immediate institutional or social response—from reprimand to physical restraint—from anyone but their crewmates (although institutional or social responses, or the implication of such, may well affect their family members).

Experimental work has been conducted on psychological-behavioral responses to extreme isolation and corresponding institutional release of this kind (e.g., Palinkas et al., 2000; Palinkas et al., 2004). Much of this work relies explicitly on analogical frameworks in 'isolated, confined, and extreme' (ICE) environments (Golden et al., 2018). However, even within ICE contexts, such research is intrinsically limited by [1] ethical constraints associated with human test subjects and [2] the impossibility of removing the tacit threat of coercive authority from such subjects. To some extent, in a non-experimental situation, we might expect deviation from normative expectations to be mitigated by the prospect of a subsequent return to Earth and to the remit of coercive authority. This problem consequently becomes more pressing in the context of attempted colonization of a non-Earth body. We lack data on how colonist populations who will be permanently separated from the source population build social systems and behavioral mores that either mimic or diverge from expectations, despite the recognition that colonization processes provide opportunity for social plasticity; Szocik et al. (2018), in their discussion of human reproduction in the Martian environment, stress the likely mutability of ethical systems in a colonization context. In general, there are severe limits to what can be known about how humans respond to an absence of coercive authority in isolated environments, and how behaviors and social forms respond to this isolation over the short to long term.

2.2. Ecological scenarios

Exploration of the solar system within Neptune's orbit will involve humans, machines, plants, and possibly non-human animals, artificial intelligences, and biotechnologically enhanced humans (Bainbridge, 2009; Mortimer & Gilliham, 2022; Pozzebon, 2024; Szocik et al., 2021) traveling through vacuum to planets and moons with exotic geochemistries (e.g., Delitsky & Lane, 2002; Lopes, 2014; Stephan et al., 2020). Terrestrial physical systems, such as the hydrosphere or lithosphere, are interlinked, sensitive both to external stimulus and to dynamism in neighboring systems, including in the biosphere (Martin & Johnson, 2012). We can infer that the physical systems of—for example, Io, Europa, or Titan—are equally likely to be responsive to external stimuli, including anthropogenic stimuli. However, we do not know what form these responses will take: how the presence of humans and their machines, associated gaseous emissions, detritus, and accompanying microbiota, will impact extant non-Earth systems (setting aside the ethical concerns regarding anthropogenic impacts on off-Earth environments (Slobodian, 2015; Stoner, 2017).

Microbiota are of particular interest here (e.g., Justiniano et al., 2023; Lopez et al., 2019; Marra et al., 2023; Santomartino et al., 2023; Tesei et al., 2022). Experimental evidence suggests the possibility of interplanetary contamination (Yair et al., 2021). It has been argued that the survival of any terrestrial organic chemical processes during a contamination event is intrinsically unlikely (Bak et al., 2017). However, organisms that can tolerate extreme environments (such as certain species of extremophile archaea or bacteria, or tardigrades, for example) are categorically able to tolerate and exploit exotic biochemical pathways that render certain terrestrial environments lethal to non-extremophile biota (Martínez-Espinosa, 2020). We do not know what effect if any, for example, the introduction of nitrogen-fixing extremophile archaea might have in the nitrogen-rich Titanian atmosphere, but survival beyond the colonization phase must at least be considered. If, for the sake of argument, translocated microbiota did not experience immediate extirpation, we have no models for the expansion and speciation of Earth-derived organisms in a non-Earth context as they experience a version of ecological release. On Earth, microbiota do not exist in isolation, but interface with inorganic matter to create biophysical systems. Ecological release of terrestrial extremophile microbiota on a Jovian or Saturnine moon could conceivably have broader and long-lasting atmospheric, cryospheric, or lithospheric effects.

Finally, and in an arguably worst-case scenario (although not all agree (Janjic, 2020), we do not have experimental data or models on the interaction between Earth-derived organisms and exobiota (if they exist). In a terrestrial context, the ethical and pragmatic cases

for preserving biodiversity have been made (Batavia & Nelson, 2017), and this reasoning can be extended to exobiota. The implications of this reasoning exceed intentional human behavior, however. To return to the previous example: if there are exobiota on Titan, and if unintentionally introduced nitrogen-fixing terrestrial extremophiles are introduced to Titan and survive, this will unavoidably have unknown and possibly negative effects on Titanian ecosystems.

The inability to accurately replicate these scenarios essentially means that knowledge of how to optimize outcomes of solar system exploration and utilization is substantially impaired, including in terms of the ethical dimension. We need means of mitigating this impairment if we aim to optimize these outcomes.

3. Ecological and behavioral analogs in island colonization

In the absence of experiments to examine how these scenarios would impact humans and extraterrestrial environments, we must turn to Earth-bound analogs or models. As some scholars have argued, the best correlate for the long-distance exploration, utilization, and colonization of the solar system by humans is the human settlement of islands in the ancient past (Finney and Jones, 1985; Finney, 2003; Fitzpatrick, 2023; Webb, 2021). This process involved the long-distance movement of small groups of people across expansive and hostile environments to reach contexts previously insulated from humans, their materials, technologies, and associated taxa. Colonization drove recursive feedbacks between insular biophysical systems and human social organization, prompting novel trajectories in behavioral, ecological, evolutionary, and physical systems. How can we examine such processes and why are islands the most suitable analog for future space colonization?

3.1. Behavioral and demographic scenarios in island colonization

Archaeological, ethnographic, historical, and genetic data reveal how island colonization affected human behavioral and demographic trends. First, and in common with most organisms (Hanski, 1998), small colonizing populations are subject to stochastic fluctuations toward extinction. The Minimum Viable Population (MVP) size for humans is undetermined (Impey,2015] estimates at least 5000 individuals for Martian colonization, although historical island data suggest this is too high), but the models support substantially reduced intrinsic viability as populations shrink below a few dozen (e.g., McArthur et al., 1976). Archaeological evidence indicates that there are multiple instances of colonizing populations experiencing extinction (e.g., Kirch, 1988; Anderson, 2001). With that said, if we consider persistence over a millennium to represent long-term persistence, human MVP is certainly below 1000 (e.g., Kirch & Yen, 1982), probably ranging from a few dozen to the low hundreds. Genetic sampling on bioarchaeological remains across the relevant contexts could indicate effective population sizes prior to local extirpation, providing empirical baselines for human MVP.

Second, isolation during a colonization phase can demonstrably result in aberrant or non-normative behavior. Documented historical examples (alongside examples from oral traditions; Anderson, 2006) include emergent 'despotic' tendencies in modern populations when removed from institutional authority (e.g., van Sittert 2015). In the case of Pitcairn in the south Pacific, colonized by a group of 28 individuals in 1790, a more or less despotic patriarchal system was accompanied by sexually abusive behavior (Scott & Staines, 2020) that had become institutionalized (encultured) over the long-term. As human populations have recognized in the past, but the results of which are more visible in smaller and remote communities like those found in the Pacific, negative biological outcomes from sexual behaviors that include consanguineity have negative biological outcomes. Hence, smaller island populations strive to connect with other islands for intermarriage, exchanging resources, and reliance in case of catastrophe (often termed the 'rescue effect'). Synthetic studies of situations of this type should reveal common patterns in specific facilitating factors of highly non-normative behavioral outcomes.

Third, population division followed by extreme isolation during the colonization phase can result more generally in highly plastic cultural responses. This happens both to material cultural but also sociopolitical structure. Material cultural change during colonization is often interpreted within an adaptive framework. However, there is support for random cultural drift that is neither maladaptive or adaptive, but an ineluctable outcome of population subdivision (Bentley et al., 2004), including random drift during colonization phases (see Crema et al., 2024). Isolation over longer periods of time can drive comparable sociopolitical change. The colonist populations of Hawai'i and Tonga, for example, were likely not arranged into formally inegalitarian or hierarchical societies, yet over a few centuries, profoundly hierarchical (perhaps 'archaic' states) societies developed in both archipelagoes (e.g., Clark et al., 2020). There are comparable examples of the evolution of emergent social structures in the Mediterranean and Caribbean (e.g., Keegan & Maclachlan, 1989).

Finally, colonization of islands by small populations can drive biocultural changes. Small, isolated island populations experience comparatively high levels of consanguinity (Villanueva et al., 2013). This can have deleterious effects through accumulating homozygosity: for example, high rates of asthma on Tristan da Cunha (Zamel et al., 1996) or color blindness on Pingelap in central Micronesia (Winick et al., 1999). More generally, it is evident that island colonization involving small or structured populations drives microevolution therein (e.g., Almeida et al., 2021).

3.2. Ecological scenarios in island colonization

Human colonization of islands promotes environmental change, and does so through a series of pathways (Braje et al., 2017). Some of these effects are predictable, and some less so. Most obviously, colonizing humans impact previously human-free environments through direct means. These can include landscape modification aimed at increasing agricultural productivity, ranging from terracing to prevent sediment loss and increase growing surface, and clearing forest or brush, to direct intervention in soil and moisture regimes

(Ladefoged et al., 2009; Quintus et al., 2016). Other types of direct impact pathway include hunting of endemic biota leading to the extirpation or extinction of species intertwined within fragile ecological systems, along with the introduction of non-native species (Athens and Ward, 1993; Braje et al., 2017; Rick et al., 2020).

Human colonization can also have indirect or otherwise unintended consequences, however, that have neutral or negative effects on productivity. For example: deforestation leads to multiple consequences (including transformations in soil moisture and chemistry), but in particular drives sediment dynamism, leading to denudation, erosion, alluviation in valleys, and deposition of terrestrial sediment in the water column, including over coral reef systems that are highly sensitive to water clarity and temperature (e.g., Kennett et al., 2006; Kirch & Yen, 1982). Landscape modification can also occur unintentionally via the introduction of non-native species: either domesticated (the domestic goat, *Capra hircus*, for example, has driven soil loss and large-scale ecological change in the insular Mediterranean (Leppard & Pilaar Birch, 2016), or unintentionally introduced species (i.e., translocated taxa). The latter can exercise profound influence over island biophysical systems. The human-introduced Pacific rat, *Rattus exulans*, for instance, is likely implicated in the extinction of endemic avifauna and palm species during the human colonization of Oceania (Athens et al., 2002; Hunt, 2006). Moreover, redistribution of nutrients, driven directly or indirectly, in this way can transform the productive potential of the landscape. This can drive changes in political economy when, for example, patchily distributed high-productivity niches develop (DiNapoli et al., 2018); or when extinctions interrupt the nutrient cycle, decreasing net nutrient availability (Doughty et al., 2015).

Finally, the biological effects of island colonization by humans are not limited to the ecological scale. As with humans, introduced taxa undergo microevolutionary change associated with small founding populations that remain genetically isolated. Examples include both domesticates (Stoffel et al., 2021) and translocated species. Indeed, the accumulation of deleterious traits in the common vole (*Microtus arvalis*) since its introduction to Orkney appears not to have greatly influenced the species' overall persistence (Wang et al., 2023).

4. Conclusions

We have only a limited understanding of the likely effects of human exploration of the solar system on both the subject and the object of exploration. The multidisciplinary study of the colonization of islands by humans offers the most robust analogs for this process. From these we know that human colonist populations are initially at risk of extinction, exacerbated homozygosity, and rapid behavioral-psychological change and, at greater time scales, broader social evolutionary change and microevolution. Conversely, we know that colonized landscapes are susceptible to a range of transformative anthropogenic processes, many of them unintended by colonizing groups but nonetheless with potentially severe ramifications. The more comparative studies we have, the more we can affect, mitigate, and govern various effects during off-Earth exploration and colonization (recognizing, in passing, that technological innovation, especially in the biotechnologies, may affect thresholds in ways that do not parallel Holocene terrestrial comparanda; gene-editing effects mitigating exacerbated homozygosity, for example).

Unfortunately, there have been no systematic studies of these analogs. For example: we know that small populations, when isolated, can experience rapid behavioral change when released from institutional or hierarchical oversight, but we do not know how small or how isolated such populations need to be for such changes to occur and at what speeds. We understand that colonization of previously human-free environments causes ecological cascades or can even lead to extinction or forced abandonment, in turn parameterizing human subsistence activity and political economy. But we do not clearly understand how ecological fragility, composition of introduced/translocated taxa, and population load interact to specify the severity of these cascades; apart from what might be inferred from the Pacific 'mystery islands' phenomenon (see Anderson, 2001) in which small, remote islands with impoverished resources were occupied by humans but did (or could) not lead to permanent settlement. Finally, we are aware that colonizing populations experience genetic drift and microevolution, though we are not aware of how severe homozygosity has to be, or how small population size can be, before populations fluctuate to zero in the medium to long term.

We call for meta-studies of these processes, which should in principle be measurable and comparable to the extent that we can offer generalizing statements about them. These studies would integrate extant human genetic data (both ancient and modern), demographic data (archaeological and historical), longitudinal insular environmental data (palynological, archaeozoological and archaeobotanical, and eDNA), with pertinent geographic variables (size, latitude, elevation, coastal complexity index, isolation index, NPP) in a robust statistical framework to better parameterize how the intersection of human colonists, their commensals, and island environments drive certain outcomes. This would result in predictive capacity that has relevance to near-term off-Earth exploration and colonization.

CRediT authorship contribution statement

Tom Leppard: Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Methodology, Data curation, Conceptualization. **Scott M. Fitzpatrick:** Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Methodology, Data curation, Conceptualization.

Declaration of Competing Interest

None.

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