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How to successfully colonize space: Lessons from island archaeology

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ABSTRACT

Humans will soon attempt to colonize astronomical bodies within, and perhaps eventually beyond, our solar system. This is intrinsically dangerous, and yet we have limited experimental means of resolving how to mitigate risk and promote long-term success in space colonization. The human settlement of islands on Earth provides the best analog for the colonization of astronomical bodies. The global pattern and process of island colonization, including which factors inhibit or promote long-term success, is well understood. Here we derive eight lessons from island archaeology that indicate means for optimizing success in refining (1) targets for space colonization and (2) the composition and behavior of the colonist group. We recommend that these lessons are incorporated into near- and long-term planning.

1. Introduction

Humans will soon attempt to permanently inhabit (colonize) astronomical bodies within our solar system and, perhaps eventually, other star systems. Long-distance dispersals with the aim of colonization have intrinsic risks. Beyond those that are technological-logistical in nature (that even transporting humans and necessary materials through space may fail), simply placing a human population on an astronomical body does not constitute success. Small, remote populations of organisms in novel and potentially challenging environments are extremely fragile for a variety of reasons. We therefore require a suitable means of evaluating what parameters promote success and failure in human colonization dynamics more generally. However, space colonization science currently lacks a body of theory with which to undertake this modeling (but see Ref. [1]).

In many respects, the archaeology of islands provides the most suitable means by which to examine this phenomenon, given that it is a subfield dedicated to reconstructing past human behavior across deep time and on a global scale. In essence, island archaeology examines how and why humans arrive at, settle on, and co-evolve with island environments. Earth's islands – small fragments of land separated from each other by the sea – are the best analogs for astronomical bodies. As such, island archaeology is the field of study best placed to supply a body of theory that relates to human colonization dynamics in general. This could be used to model factors predicting success versus failure in the human colonization of space.

There have already been several studies that link archaeology to space colonization science. These have either taken the form of applying heritage management practices to human materials in space (e.g., Ref. [2]), the evaluation of our species' impact on extraterrestrial ecosystems [3–5], and the recognition that astronomical bodies represent depositional contexts; that is, those that have the potential to preserve archaeological traces [6,7]. Research has also stressed the analogy between colonization of terrestrial environments and those that are extraterrestrial [8–10]. We have argued [11] that remote islands on Earth settled by humans since about 50 kiloyears ago (kya) provide the best analogs for bodies within and beyond our solar system; and that the human colonization of these islands provides 'natural experiments' through which we can better understand the likely stressors faced by humans and environments during colonization forays into space.

Here we move beyond highlighting comparability, and utilize island archaeology – which draws on artifactual, environmental, and genetic and other biological data – to derive lessons for maximizing the success of human colonization of both near, and further, space. To do so, we consider the archaeological record of island colonization from the Upper Palaeolithic period (about 50 kya) onwards. We divide our discussion into two sections. First, we consider physiographic factors – relating to the physical organization of colonized environments – that predict

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successful colonization. Second, we consider biocultural factors, or those relating to the properties and behavior of the colonizing organism, that predict successful colonization. We subsequently propose ideal colonization environments and dynamics that should most effectively promote long-term success in space colonization.

What we do not do in this paper is consider technological-logistical risks and failure of colonization prior to arrival in the novel environment. Archaeological data lend themselves to studying human behavior that is evident in human material traces (such as artifacts, structures, or landscape modifications), and colonization that has failed before arrival in a new environment tends not to have a material signature. However, we do stress that, in the span of our species crossing water bodies to reach novel environments, pre-landing failure has likely been frequent (e.g., see Refs. [12,13]), a feature that will also characterize human colonization of astronomical bodies.

2. Physiographic factors that predict successful colonization

The study of human colonization dynamics on Earth suggests that physiographic characteristics of both the source and novel environments are major predictors in long-term success (physiographic factors can also impinge on biocultural factors, so our distinction between the two here is a device to structure our discussion, not an absolute). We can consider these factors according to the following categories.

2.1. Distance from source body

Island archaeology suggests that the closer the source body is to the landmass to be colonized, the higher the likelihood of successful long-term colonization. That is, a metric known as the *isolation index* of a given island (calculated as the sum of the square roots of distance to nearest equal-sized or larger island, nearest island group, and nearest continent [14]) is a predictor of how long ago an island was colonized [15]. This is partly because – in the absence of remote-sensing technology allowing the evaluation of a potential colonization target from distance – proximity, like greater size, increases the chances of discovery (e.g., Ref. [16]). This is because proximity, like size, increases the likelihood of a chance encounter during exploration.

However, this is not the only reason that proximity to the source body is relevant in successful colonization. It is also the case that proximity (1) reduces the amount of space, and consequently of time, in which technological-logistical failure can occur on the way to the novel environment. While the archaeological record is not sensitive to these failures, other types of data support this. Proximity by strict definition also (2) places the colonist population closer to the source population. This facilitates participation on the part of the colonist population in a wider *metapopulation*, a group of populations that are spatially discrete but interact genetically [17]. Access to a metapopulation significantly boosts demographic robusticity. Indeed, early colonization horizons on Earth show evidence for high degrees of interaction (and consequently genetic exchange) in the immediate aftermath of colonization [15]. This is probably because metapopulation engagement, via the 'rescue effect' [18], decreases exposure to deleterious homozygosity (i.e., 'genetic rescue' [19]). Being close to the source population also provides opportunities to trade and exchange resources and ideas and promotes more rapid recolonization in the case of catastrophic demographic failure to the point of extirpation (i.e., population bottleneck).

We should stress here that proximity can be viewed as technologically relative. Increased speed or range of a vessel conceptually reduces the distance between landmasses. To the extent that spacecraft achieve different speeds, astronomical bodies become more or less effectively remote. Orbit and relative motion also complicate this calculation; within-system, but also between systems [20]. This does not affect the primacy of proximity as a determinant, however, but only indicates that it is not a fixed quality. It is worth noting that even more technologically sophisticated modes of transportation do not guarantee easy or any access at all points in time. There continue to be significant logistical challenges that many islanders face today in different parts of the world, particularly the Pacific.

Accordingly, we derive the first lesson from island archaeology for space colonization: the closer the body to be colonized is to the source population (and indeed other populations), the more likely is long-term success.

2.2. Size of colonization body

Island archaeology suggests that the size of the target surface is a major predictor of successful long-term colonization. This traditionally has been understood as a function of size, like proximity, driving *conspicuousness* during the discovery phase (e.g., Ref. [16]). That is, during exploration, size makes an island a more obvious and readily sensible entity. However, it is also clear that size influences colonization success along other pathways. For example: the configuration of the Mediterranean is such that overall island conspicuousness is high, but a preference for larger islands is still evident since 20 kya [21]; in the Caribbean, larger islands witnessed earlier colonization despite higher isolation indices [22,23]. In these instances, the influence that size exerts beyond discovery-phase effects is primarily demographic-ecological [24]. Firstly, all other factors being equal, larger areas can support greater – and thereby more robust – colonizing populations given the wider array of resources available (e.g., freshwater). Beyond colonist demographics, larger surfaces with organic systems tend to support more substantial and more diverse such systems (i.e., ecologies) through the *Species-Area Relationship* [25], which captures the observation that larger areas support more species. Bigger ecologies also provide more robust energetic support for higher-trophic tier consumers, such as humans, driving demographic robusticity in those tiers. There is also a relationship between ecological size and ecological diversity and 'ecosystem services' [26]. To the extent that ecosystem services are a net positive for human populations, larger ecosystems provide greater benefit. Related to this, big, diverse diverse ecologies tend towards greater resilience [27], and resilience is also a net positive during colonization.

It is not relevant that surfaces subject to colonization do not possess ecological systems in that they might be devoid of organic chemistry. We are assuming that introduction of ecologies premised on organic chemistry is likely during the colonization phase. An extant exobiotic ecology is an analytic challenge, as it is not clear if the Species-Area Relationship (or, indeed, other terrestrial ecological patterns) would exist [28].

On terrestrial colonization surfaces, size tends to correlate with geological diversity (and thereby with pedological diversity) (e.g., Ref. [29]). This drives diversity of mineral resources, which in turn parameterizes technological development and output. Of the larger rocky bodies of our solar system, surface and other formation processes, planetary differentiation, and unique post-formation histories (e.g., the hypothesized Theia impact) have resulted in essentially comparably varied surface geologies. However, below a certain size threshold (e.g., 4 Vesta), geologic diversity seems to generally decrease with size (although this does not exclude the possibility of a correlation between size and chemical complexity above this threshold; e.g. Ref. [30]). Pedologic structure and diversity also influences colonization success. Soils are a function of lithosphere-biosphere interaction, so on an astronomical body with no organic chemistry we would not expect soils. However, assuming that soils developed following the introduction of terrestrial organics, they would tend towards greater diversity on larger astronomical bodies.

The main factor that differentiates size being a determinant of non-Earth colonization processes from terrestrial colonization processes is that gravity across Earth's islands is uniform. The corollary of increased size for terrestrial colonization surfaces is increased mass for extraterrestrial colonization surfaces. Associated high or very high gravitational

loads will impose costs on colonists that could exceed the benefits of size. Related, with terrestrial colonization surfaces greater size tends to equate with greater elevation, which is in turn a driver of ecological diversity. Higher gravitational loads on rocky planets result in flatter surficial topographies, reducing ecological diversity. However, if we assume likely colonization of space bodies within certain gravitational thresholds (from Mercury-sized to small super-Earths), these considerations are less pressing.

Accordingly, we derive the second lesson from island archaeology for space colonization: the larger the body to be colonized, the more likely is long-term success, up until the point that associated gravitational loads become too damaging to human physiology.

2.3. Geometry of neighboring bodies

Island archaeology suggests that having additional terrestrial bodies in proximity to the colonized surface, and in configurations that facilitate access and communication, increases the likelihood of successful long-term colonization. For example, islands that witness higher rates of permanent localized extirpation in the Pacific tend, in general, to be isolated rather than existing in archipelagic configurations [31]. This can be explained in the same terms that account for why size and distance are predicting factors. Additional landmasses in proximity allows access to more diverse, and in sum more substantive, resource environments. They allow subsidiary colonization of additional target surfaces, allowing the local development of a metapopulation and facilitating the rescue effect. Conversely, neighboring bodies allow for evacuation opportunities in the face of large-scale environmental impacts in the initial colonization environment. As regards astronomical bodies, this is of course complicated by orbit, which generates dynamism in the configuration of bodies in space that does not exist in terrestrial colonization environments (although clearly also allows for lunar bodies in orbit, which may in turn represent viable colonization environments). With that said, crossing interstellar space for the purposes of colonization would render subsequent intra-system distances trivial.

Accordingly, we derive the third lesson from island archaeology for space colonization: the greater the number of additional astronomical bodies in proximity to the body to be colonized, the more likely is long-term success, especially if those bodies have been colonized or are suitable for colonization.

2.4. Resources

Island archaeology suggests that, while resource distribution does not have immediate implications for survivability of a colonizing population (in part because colonists often bring with them domesticates), it does have long-term constraining effects on political evolution. Specifically: there is evidence that wide rather than clustered resource distribution allows broad access that should depress wealth inequalities. Conversely, clustered resources allow restricted access and control, which in turn drives emergent wealth inequalities (e.g., Ref. [32]). However, for this to apply to bodies in space, we would need to assume that the colonizing institution or institutions have economic independence from the source population for these differences to be material.

Accordingly, we derive the fourth lesson from island archaeology for space colonization: if the colonists have economic independence from the source population, then broadly (rather than narrowly) distributed resources should prevent deleterious exaggerated wealth inequality.

3. Biocultural factors that predict successful colonization

Alongside physiographic conditions, biocultural factors – those pertaining to the source population, its organization, and its behavior during the colonization process – are major determinants of long-term success. Again, we stress that physiographic conditions can affect biocultural conditions, so this is not a rigorous distinction. We can consider biocultural factors according to the following categories.

3.1. Population structure

Island archaeology suggests that population structure is a major predictor of successful long-term colonization. Specifically, size, composition, and distribution are influential factors.

Colonizing populations should be as large as possible without posing a resource strain or implicating ecological collapse. This is for several reasons. First, larger populations are proportionately less exposed to stochastic effects, and as size increases, the chances of fluctuating to zero decreases (e.g., Ref. [33]). Second, larger populations are intrinsically less exposed to risks derived from homozygosity (e.g., Refs. [34,35]). The advantages of scale are clear; the colonization of Sahul (the palaeo-continent now represented by Tasmania-Australia-New Guinea), for example, successful over a decamillennial scale, is now modeled to have involved at least 1300 to 1500 individuals [36]. Conversely, isolated populations derived from historically small colonization events exhibit autosomal recessive disorders: elevated levels of Primary Carnitine Deficiency in the Faroes [37]; Bardet-Biedl Syndrome in Newfoundland [38]; the BRCA2 cancer-associated mutation in Iceland [39]; and color blindness among the Pingelapese in central Micronesia [40]. It is not clear whether, in the absence of genetic rescue from the metapopulation, these communities would persist over decamillennia. In these cases, we can guess, but do not know, that the founder community had a high degree of consanguinity, leading to a high inbreeding coefficient. In the case of the recent colonization of Pitcairn Island by Fletcher Christian and the mutineers of *HMS Bounty* in 1789, and the subsequent colonization of Norfolk Island, the female component of the colonization event had a comparatively high degree of consanguinity, and there are resulting homozygous effects [41,42].

In this context, we note that viewing demographic size as associated with long-term success through simply considering the necessary size to advance to the next generation is probably erroneous (as, e.g., Marin and Beluffi [43] with their minimum number of 98). In any case, there are discrepancies surrounding the modeling of the size of a human population necessary simply to reproduce itself (e.g., Ref. [44]). Prioritizing overall genetic health and low homozygosity drives minimum population sizes much above these estimates. In this context we note that modeled MVPs for great apes (e.g., *Pongo*) produce numbers in the low thousands [45].

The vast majority of terrestrial colonization events have involved populations were broadly culturally homogenous. Only comparatively recently have colonization events involved widely disparate heterogeneous populations (e.g., the European colonization of the Americas), to the extent that we cannot evaluate whether cultural homogeneity versus heterogeneity drives long-term success during colonization events. We note that there is a long tradition of support for cultural homogeneity as a driver of cohesion and epistemic consensus (e.g., Ref. [46]). However, cultural heterogeneity may also bring together diverse knowledge systems and problem-solving approaches, potentially increasing adaptability and innovation. There is, for example, evidence that colonizing populations benefit from broad distribution of skill sets and cultural knowledge which is evident in continued and complex (but somewhat varied) traditions of megalithic architecture such as ceremonial *marae* in East Polynesia [47,48] and boat building and wayfinding techniques that allowed for continued voyaging [49,50]. To the extent that heterogeneity correlates with lower consanguinity, it may offer biological as well as epistemic/cultural benefits.

Accordingly, we derive the fifth lesson from island archaeology for space colonization: the colonist population should be as large as possible within technological-ecological limits, ideally over 1000 individuals. It should be genetically (and likely also culturally) heterogeneous.

3.2. Population behavior

Island archaeology indicates that colonist behavior profoundly influences long-term success or failure during colonization events. It is helpful to divide behavior into demographic and environmental categories.

How populations should behave in terms of demography is emergent from previous considerations. Specifically, colonists should build and maintain metapopulation links with the source population and sister colonist populations. The importance of maintaining connections to ensure long-term survival is evident from the archaeological record [51,52]: in the Pacific, exchange systems – like the *sawei* ("food basket" in Ulithian) system in central Micronesia [53,54] – developed in areas where there was an abundance of low-lying islets separated by tens or hundreds of kilometers. Connections were established between geologically distinct islands to create and/or maintain social relations, and obtain resources not found in their respective islands (e.g., pottery or clay, stone, timber for atolls; shell valuables and basketry for volcanic islands). These interactions were galvanized within island regions here and elsewhere to mitigate stochastic environmental effects and provide demographic buffering.

However, island archaeology suggests other advantageous behavioral adaptations; specifically, continued exploration for colonization niches as a means of buffering against localized Malthusian ceilings, instantiated as selection-driven range-expansion [55]. Essentially, this means that continuous colonization, moving increasingly further from the source population, can represent an adaptive advantage in that it provides an ever greater number of growing colonist populations that are connected to one another but that ultimately leads to cultural and biological differences (e.g., language diversity, founder effects).

Repeatedly, during island colonization on Earth, colonists have introduced novel lifeforms, including pathogens; targeted specific types of resources; and regularly undertaken large-scale and selective modification of island environments. These behaviors together have routinely driven unintended environmental consequences that have had negative effects on colonist populations [56]. For example: deforestation following colonization is a regular outcome, with domesticated species implicated alongside commensals (e.g., Ref. [57]), acting in concert with intentional human clearance for fuel or food-production. Vegetation loss has a series of effects, the most substantial of which is soil erosion. This, in turn, increases sediment loads downslope, including sediment transport into inshore marine environments, rearranges nutrient surfaces, exacerbates weathering upslope, and transforms hydrological systems (e.g., Refs. [58–60]). Evidently, in abiotic environments in space, colonists will not have biotic impacts that will affect biophysical systems (such as the root-soil interface). However, to the extent that physical systems are interlinked and effects cascade between them, any type of large-scale and selective modification of a colonized environment has the potential to result in unintended but severely deleterious environmental consequences.

Accordingly, we derive the sixth, seventh, and eighth lessons from island archaeology for space colonization: the colonist population should build and maintain links with as many other populations as possible; should continue iteratively sending out subsidiary colonist populations; and should attempt to preserve extant ecosystems or physical systems so as to not drive change in related systems.

4. Discussion

Over three decades ago, Finney [61] suggested the history of the colonization of oceanic islands is an ideal analog to understand current and future attempts to colonize our solar system, and beyond. In this spirit, we reviewed the archaeological record of the colonization of Earth's islands, which allows us to derive eight lessons for space colonization: specifically, about both ideal colonization environments and populations.

(1) The closer the body to be colonized is to the source population (and indeed other populations), the more likely there is to be long-term success.
(2) The larger the body to be colonized, the more likely there is to be long-term success, up until the point that associated gravitational loads become too damaging to human physiology.
(3) The greater the number of additional astronomical bodies in proximity to the body to be colonized, the more likely there is to be long-term success, especially if those bodies have been colonized or are suitable for colonization.
(4) If the colonists have economic independence from the source population, then broadly (rather than narrowly) distributed resources should prevent deleterious exaggerated wealth inequality.
(5) The colonist population should be as large as possible within technological-ecological limits, ideally more than 1000 individuals. It should be genetically (and likely also culturally) heterogeneous to avoid founder effects.
(6) The colonist population should build and maintain links with as many other populations as possible to increase survival and ensure exchange relationships.
(7) The colonist population should continue iteratively sending out subsidiary colonist populations to maximize survivability and increase diversity.
(8) The colonist population should attempt to preserve extant ecosystems or physical systems so as to not drive change in related systems.

To this, we necessarily must add specifics that do not affect terrestrial colonization. For example, we also need to consider atmospheric composition, proximity to local stars, and tidal locking. With that considered, we can start to develop propositions about the ideal colonization environment. It would be: close to the source-population (initially Earth); surrounded by further potential colonization environments; large enough to support a suitable population, diverse ecosystems and mineral resources (including water and, potentially, organic material), yet not so large that gravity has a deleterious effect on colonists; with these resources broadly, rather than narrowly, distributed.

With this information, it becomes possible to evaluate colonization environments in our own and in local star systems. Locally, it suggests some more, and some less, viable environments. Mars, as comparatively large and close to Earth, is an obvious candidate. Some outcomes are less obvious; the Galilean Jovian moons are more suitable colonization targets than Saturn's moons (or the non-Galilean Jovian moons), which in turn are preferable to the Uranian or Neptunian moons. The asteroid belt has advantages in terms of sheer number of colonization targets, but these have strong disadvantages in terms of size. At the scale of the Local Interstellar Cloud, these lessons permit further discrimination. For example: Barnard's Star (5.96 ly) has four confirmed planets, making it a target-dense colonization environment that is close to the source population on Earth. However, all four planets are small – all less than half an Earth mass – rendering them undesirable; and all four lie too close to their star for surficial liquid water (i.e., lie interior to the habitable zone) [62]. Lacaille 9352/GJ 887 is further from the source population (10.72 ly) and has fewer planets, but these are large (both super-Earths at 4.2 ± 0.6 and 7.6 ± 1.2 Earth masses), and one, GJ 887c, is close to the inner edge of the habitable zone [63]. GJ 1061 has three likely rocky planets, all larger than Earth but under two earth masses, and of which are within or proximate to the habitable zone. This makes this system a comparatively target-rich colonization environment despite the greater distance from source population (11.98 ly) [64]. These examples are purely illustrative, and we do not exhaustively evaluate potential colonization environments here. However, it should be possible to weight these criteria and subsequently model quantitatively the relative colonization suitability of all local star systems.

The ideal colonizing population would be large; we would estimate

at least 1000 colonists, and ideally more. In addition, assuming that the colony would not be in a position to immediately establish daughter colonies, then several colonies should be established in a given area of space simultaneously. Each population would have low homozygosity, and consequently would ideally have low consanguinity. This would correspond with a high degree of cultural heterogeneity and associated wider collective knowledge- and skill-sets. All this taken in sum implies an enormous logistical operation, likely exceeding current planning – but attempts at colonization below this demographic scale risks failure over the long term.

5. Conclusions

If we assume that colonization of non-Earth bodies remains a policy goal, then we need to refine our understanding of ideal colonization scenarios. Islands are the best analogs we have for astronomical bodies, and island archaeology has developed a broad understanding of the patterns of successful island colonization by humans. This allows us to derive lessons for optimizing success during space colonization. We recommend (1) that these lessons are incorporated into near- and long-term planning, and (2) that further synoptic study of 'natural experiments' of human colonization over the last 50 kya will further parameterize what factors contribute most substantially to long-term colonization success.

CRediT authorship contribution statement

Thomas P. Leppard: Conceptualization, Methodology, Writing – original draft, Writing – review & editing. **Scott M. Fitzpatrick:** Conceptualization, Methodology, Writing – original draft, Writing – review & editing. **Justin A. Holcomb:** Conceptualization, Methodology, Writing – original draft, Writing – review & editing.

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