AN ASTROECOLOGICAL APPROACH FOR PLANETARY PROTECTION OPERATIONS AT MARS.

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Introduction: In ecology, habitat suitability index (HSI) models are quantitative frameworks for evaluating the degree to which an environment can support a specific species or model organism [e.g., 1, 2]. These indices apply known environment-species relationships, such as temperature tolerances, to predict survival, reproduction, and development, as well as the potential for species recruitment. Recently, [3] suggested applying HSIs to planetary science in order to resolve the habitability of extraterrestrial environments in a consistent and quantitative manner. Their work has gained support from the ecology community, as highlighted in a review article by [4] advocating for a new branch of astrobiology, astroecology. Indeed, similar approaches have been leveraged in planetary protection policies, whereby, e.g., species-environment relationships have been used to define Special Regions on Mars [e.g., 5].

Given the information available from orbiters, landers, and general circulation models (GCMs), HSIs can provide insights to the present-day habitability of the martian surface and shallow subsurface, which can help inform planetary protection considerations. Furthermore, GCMs under different obliquity periods along with HSIs can be used to assess dynamic habitability and thus help to identify areas that have consistently experienced suitable conditions. Because Mars may presently support (meta)stable brines [e.g., 6,7], sites where they occur may provide the liquid water environment necessary for life, as well as shielding from radiation [e.g., 8]. Two environmental parameters that control brine stability, ambient temperature (T) and water activity (a_w), which at equilibrium is related to relative humidity with respect to liquid (RH_l), also impact the biological potential and are used to define Special Regions on Mars. MEPAG defines a Special Region as an environment that can host brines with water activity $a_w > 0.6$ and simultaneously temperatures $T > 255$ K [5]. A recent NASEM study, though, advocates for stricter limits of $a_w > 0.5$ and simultaneously temperatures $T > 245$ K [9]. Thus, these environmental parameters can be used to simultaneously assess brine stability, biological suitability, and help guide the crewed and robotic exploration of Mars.

Importantly, landed meteorological packages have demonstrated that the hyperarid conditions on Mars lead to an inverse relationship between T and RH_l (e.g., Figure 1). On Mars, when $T \leq 215$ K, $RH_l > 50\%$ and when $T \geq 240$ K, $RH_l < 5\%$. Such conditions strictly confine the times when surficial conditions may be suitable to terrestrial-like life, as well as when brines are stable.

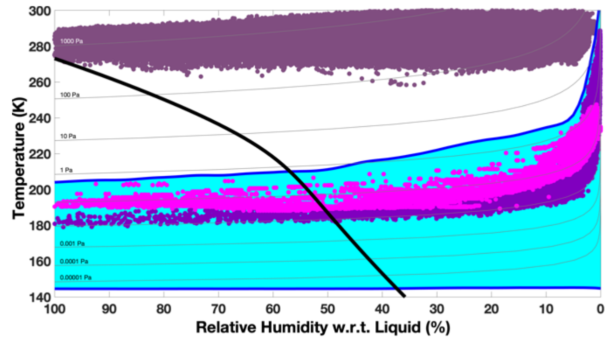

Figure 1: Temperature and relative humidity measurements from Phoenix (magenta) and MSL (purple) compared with the Atacama Desert (lavender). For context, the possible combinations of conditions predicted by the GCM MarsWRF [10] is shown in cyan. The light gray lines are isobars of water vapor pressure and the solid black line is the ice line ($RH_{ice} = 100\%$).

HSI Development: Here we developed and validated two HSI models based on species-environment relationships dependent on T and a_w. The Mass-Energy Habitat Suitability Index (MEHSI) model follows the framework proposed by [3] in which habitability is proportional to the bioavailable mass and energy. The Mars Aqueous Habitat Suitability Index (MAHSI) model is based on a distance metric calculated in T and RH_l phase space [11] that is informed by the T and a_w used in the definition of martian Special Regions [5].

Validation: The HSIs were validated against net primary productivity (NPP) from global terrestrial observations [12], as well as microbial biomass and metabolic activity data from an often-used Mars analog, the Atacama Desert [13-15]. As shown in Figure 2, we found that both the MEHSI and MAHSI models are positively associated with NPP, having a Spearman's Rank Correlation Coefficient (ρ) of 0.69 and 0.61, respectively, suggesting a strong, positive monotonic association. We additionally tested for associations with T and RH_l individually and found $\rho = 0.2$ and 0.43, respectively. Thus, although we found that T and RH_l are necessary to model NPP through MEHSI and MAHSI, they are individually not sufficient to predict global NPP values. Our findings suggest a coupled model approach offers improved results. We also compared against microbial activity data from the Atacama Desert and found that MEHSI and MAHSI are also well associated with measured bioactivity. Periods when there was no correlation are explained by unusual rain events not included in the climate data used for this study. Thus, there is evidence that both models provide information for the prediction of plant and microbial activity on Earth.

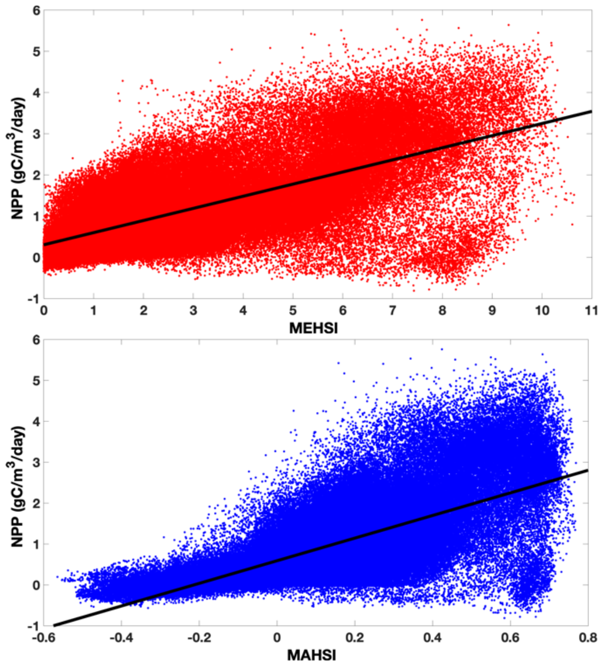

Figure 2: Land NPP as a function of (top) MEHSI and (bottom) MAHSI. The black solid line is a least squares fit.

Application: To conduct global HSI calculations, we used the hourly modeled surface temperature and water mixing ratio, which was translated to RH_l, from MarsWRF at a 5° resolution [10]. Additionally, we used experimentally-verified brine stability models [e.g., 6,7] to simultaneously consider locations where (meta)stable brines may form and persist through the deliquescence of calcium perchlorate, a Mars-relevant salt with the lowest known eutectic temperature. To consolidate both models, we found the annual average MEHSI and MAHSI for each grid location, *z*-score normalized the global map and added the results such that areas that are consistently above the global average are highlighted. In Figure 3, we show the results overlain onto a MOLA shaded relief map.

We found that both HSI models suggest the northern martian hemisphere is on average more suitable for life than the southern hemisphere, relative to temperature and water activity. The most habitable brines that may presently occur on the surface of Mars experience T=213 K and RH_l=60%. Although the equilibrium water activity of such a brine (a_w =0.6) can be tolerated by some organisms [16], the low temperature likely results in slow metabolic rates [17]. Out of the landed NASA missions, we found that Viking 2 was at a location that may have permitted brine formation [18] and experienced above global average HSI values.

We propose that ecological frameworks, such as HSIs, paired with brine formation models, may provide insights for planetary protection operations at Mars.

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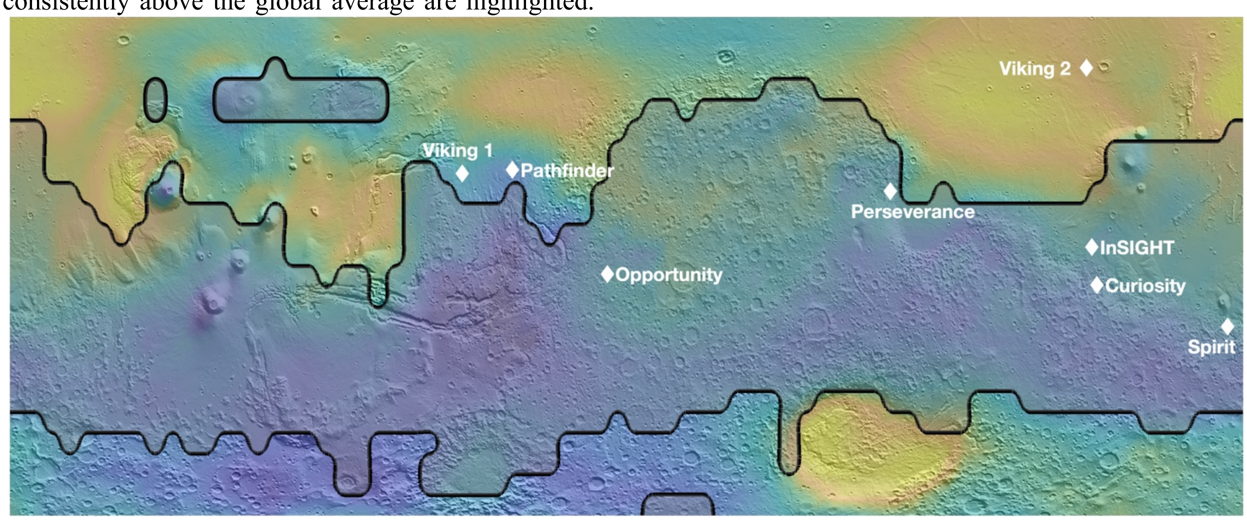

Figure 3: Combined annual average MEHSI and MAHSI overlain onto a MOLA shaded relief map. Above average HSI values are in warm colors while below average values are in blue. Black contours and corresponding grayed out regions denote areas where a calcium perchlorate brine formed through deliquescence is not (meta)stable [7]. White diamonds denote landed missions.