A GENERAL MASS-ENERGY HABITABILITY MODEL. Abel Méndez[1], Dirk Schulze-Makuch[2], Guillermo Nery[1], Edgard G. Rivera-Valentín[3], Alfonso Dávila[4], Ramses Ramírez[5], Tana Wood[6], Amy D. Rodríguez García[1], Alvin Soto Soto[1], Shakira E. González Villanueva[1], Stephanie M. Rivera Saavedra[1], Gretchen J. Maldonado Vazquez[1], Edwin Colon Acosta[1], Valerie M. Cruz Mendoza[1], Jessica K. Crespo Sanchez[1], and Nahiomy Estevez Mesa[1]; [1]Planetary Habitability Laboratory, University of Puerto Rico at Arecibo (abel.mendez@upr.edu), [2]Technical University Berlin, Germany (schulze-makuch@tu-berlin.de), [3]Lunar and Planetary Institute & Arecibo Observatory, USRA, Texas (ervalentin@usra.edu), [4]NASA Ames Research Center, California (alfonso.davila@nasa.gov), [5]ELSI, Japan (rramirez@elsi.jp), [6]US Forest Service, Luquillo, Puerto Rico (tanawood@fs.fed.us).

Introduction: The study of planetary habitability is an important subject of astrobiology [1]. Habitability is generally defined as the suitability of environments for life. Since 2007 astrobiologists have been proposing quantitative definitions of habitability, but there is no consensus yet [2, 3, 4]. Some of these definitions correlate habitability with the mass, energy, or the state of the environment for life. Yet, the basis for defining and measuring habitability was established more than three decades ago by ecologists [5, 6, 7].

Habitability is formally known in ecology as *habitat suitability*. The Habitat Suitability Index (HSI) was developed by the US Fish and Wildlife Service as part of their Habitat Evaluation Procedures (HEP) to standardize the definition and measure of habitability among ecologists [5]. The index involves using the same key habitat components to compare the ratio of existing with optimum habitat conditions for a species or community of interest. The HSI value obtained by this ratio should be linearly correlated with the biological carrying capacity. In this context, the carrying capacity can be defined as the maximum available resources in the environment to support life.

The HSI as originally defined is not extendable to the field of astrobiology. The spatial and temporal scale (*i.e.*, microenvironments to planetary scales) together with the life forms under consideration (*e.g.*, simple or complex life) makes generalization and applications difficult. Initial efforts for exoplanets, like the Earth Similarity Index (ESI) and the Planetary Habitability Index (PHI), were inspired by the HSI [8]. The ESI and PHI are complementary indices of similarity and habitability, respectively. Later developments extended or improved versions of similar indices [9-17].

Model Description: We propose a general habitability model based on an extension of the carrying capacity as a habitability proxy, but proportional to the mass and energy available for life within an environment. The environment is then constrained by a desired spatial and temporal scale (*i.e.*, the ecological quadrat), from microenvironments to planetary scales. The mass and energy habitability (ME-habitability) H is generally given by

$$H = qME \tag{1}$$

where M and E are the total mass an energy in the system, respectively, and q is a quality factor or the fraction of the total mass and energy available for life. Therefore, a change in habitability is due to a change of the mass, energy, or quality of the environment for life.

The q factor is a unitless value between zero and one that summarizes the net effect of many other factors on the quantity and quality of the environments for life in terms of both energy and mass. In general, q can be expressed as the product of other factors.

The ME-habitability is an extensive property, but sometimes we are interested in its rate of change or its spatial density. The change in habitability per unit of space and time, the ME-Habitability flux, is given by

$$\frac{\partial^2 H}{\partial s \partial t} = \left(\frac{1}{q}\frac{\partial^2 q}{\partial s \partial t} + \frac{1}{M}\frac{\partial^2 M}{\partial s \partial t} + \frac{1}{E}\frac{\partial^2 E}{\partial s \partial t} \right) H \tag{2}$$

where t is time and s is the space of interest (*e.g.*, an area or volume). Equation 2 can be used to solve for the habitability given that other environmental fluxes are known.

In principle, environments are usually compared under equal space-time dimensions, but this is not always desirable, *e.g.* when comparing the global surface habitability of planets of different sizes or ages. The hardest problem in our definition is to estimate q because it is highly dependent on the life form under consideration. Also, M and E might be difficult to estimate for large regions.

In practice, it is better to normalize equation 1 with respect to some reference environment so that H becomes an index between zero (*i.e.*, non-habitable) and one (*i.e.*, maximum habitability). Thus, the normalized habitability then becomes

$$H = \frac{qME}{q_o M_o E_o} \tag{3}$$

where q_o, M_o, and E_o are the corresponding reference values. Equation 3 simplifies the calculation of H since some factors might cancel out with the reference environment.

Application and Validation with Earth: We derived specific solutions of the ME-Habitability for phototropic primary producers in superficial terrestrial and aquatic environments as a function of temperature, precipitation, and dissolved organic matter. The habitable space under consideration is a cubic meter centered at the transition between the atmosphere and the land or water layer. The temporal scale is one year. The reference environments are a tropical rain forest (*e.g.*, El

Yunque in Puerto Rico) and a swamp or wetland. These are the most habitable biomes on Earth with the largest biological productivity per unit of space and time. Starting with equation 3, we derived equations for both land and water habitability H_{land} and H_{water} as

$$H_{\text{land}} = \left(\frac{p}{p_o}\right)^{\frac{1}{3}} \left(\frac{T}{T_o}\right)^{4} \quad H_{\text{water}} = \left(\frac{C}{C_o}\right)^{\frac{1}{3}} \left(\frac{T}{T_o}\right)^{4} \qquad (4)$$

where p is the mean annual land precipitation, C is the mean concentration of dissolved organic matter in water, and T is the land or water mean annual temperature. The terms in the denominators are the corresponding reference values for tropical rain forests and swamps.

We validated our land and water habitability from equation 4 using the Net Primary Productivity (NPP) of 12 terrestrial biomes and the open ocean as habitability proxies [18, 19]. We found that our ME-Habitability definition is linearly correlated with NPP (see figure 1). This correlation is not surprising since our equations are similar to empirical formulations that have been used to estimate the global terrestrial productivity [20, 21, 22].

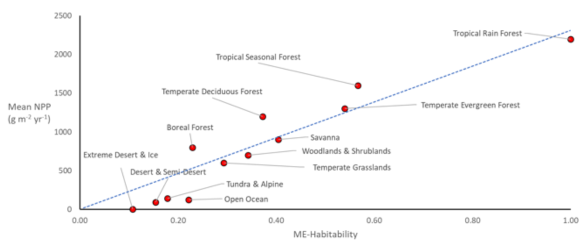

Fig 1. Correlation between mean annual net primary productivity (NPP) and ME-Habitability for some terrestrial and aquatic biomes.

Applications to Planets: We also derived from equation 3 a global ME-Habitability model based on stellar flux F, planet radius R, and ocean fraction f, using present-day Earth as the reference environment. The global habitability H_{global} is given by

$$H_{\text{global}} = \left(\frac{F}{F_\oplus}\right) \left(\frac{R}{R_\oplus}\right)^{4} \left[\frac{f\,(1-f)}{f_\oplus\,(1-f_\oplus)}\right]^{\frac{1}{3}} \qquad (5)$$

where the denominators are the terrestrial values. This equation estimates an upper limit for planetary habitability assuming that the planet has a similar land, ocean and atmosphere composition as Earth. The general trend from this equation is that the suitability of rocky planets to sustain large biospheres increase with the fourth power of their radius given that all other conditions are similar to Earth. Therefore, planets slightly larger than Earth (Super-Earths?) might be much more habitable (*i.e.*, support a larger biosphere).

The ocean fraction f is currently unknown for any exoplanet, but there are estimates for early Mars [23]. From equation 5 we estimate that early Mars with an ocean (~4.5 Gya) had no more than 2.5% the habitability of Earth today. This small number has negative implications on the ability of any early martian biosphere in transforming its planet (*e.g.*, change the atmosphere).

Conclusion: A general Mass-Energy habitability metric was constructed to characterize the potential habitability of environments based on their mass and energy available for life. Equation 3 can be used to calculate the habitability of a system for the environmental variables, and the spatial and temporal scale of interest. Our approach was validated with terrestrial and aquatic biomes using NPP as the habitability proxy and we are working on further validation with many other examples.

Habitability metrics, like the one proposed, can be used to identify and prioritize targets of interest, simplify our understanding of habitable environments, and compare real or simulated environments (*e.g.*, climate models). A common misconception is that these indices need to consider all environmental factors to be useful. Habitability is always evaluated by parts to understand the individual contribution of one or more environmental factors. A library of indices is usually constructed to characterize the net habitability of a system.

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