HABITABILITY MODELS FOR PLANETARY SCIENCES. A. Méndez[1], E. G. Rivera-Valentín[2], D. Schulze-Makuch[3], J. Filiberto[2], R. Ramírez[4], T. E. Wood[5], A. Dávila[6], C. McKay[6], K. Ortiz-Ceballos[1], M. Jusino-Maldonado[1], N. J. Torres-Santiago[1], G. Nery[1], R. Heller[7], P. Byrne[8], M. J. Malaska[9], E. Nathan[10], M. F. Simões[11], A. Antunes[11], J. Martínez-Frías[12], L. Carone[13], N. R. Izenberg[14], D. Atri[15], H. I. Carvajal Chitty[16], P. Nowajewski-Barra[17], F. Rivera-Hernández[18], C. Brown[19], K. Lynch[2], D. Catling[20], J. I. Zuluaga[21], J. F. Salazar[22], H. Chen[23], G. González[5], J. M. Kashyap[24], J. Haqq-Misra[25], [1]Planetary Habitability Laboratory, UPR Arecibo, USA (abel.mendez@upr.edu), [2]Lunar and Planetary Institute, USRA, USA, [3]Technical University Berlin, Germany, [4]Earth-Life Science Institute, Japan, [5]International Institute of Tropical Forestry, USDA Forest Service, Puerto Rico, USA, [6]NASA Ames Research Center, USA, [7]Max Planck Institute for Solar System Research, Germany, [8]North Carolina State University, USA, [9]Jet Propulsion Laboratory / California Institute of Technology, USA, [10]Brown University, USA, [11]State Key Laboratory of Lunar and Planetary Sciences, China, [12]Instituto de Geociencias (CSIC-UCM), Spain, [13]Max Planck Institute for Astronomy, Germany, [14]Johns Hopkins Applied Physics Laboratory, USA, [15]Center for Space Science, New York University Abu Dhabi, United Arab Emirates, [16]Universidad Simón Bolívar, Venezuela, [17]Fundación Ciencias Planetarias, Chile, [18]School of Earth and Atmospheric Sciences, Georgia Tech, USA, [19]Macquarie University, Australia, [20]University of Washington, USA, [21]Institute of Physics / FCEN - Universidad de Antioquia, Colombia, [22]GIGA, Escuela Ambiental, Facultad de Ingeniería, Universidad de Antioquia, Colombia, [23]Northwestern University, USA, [24]Jyoti Nivas College, Bengaluru, India, [25]Blue Marble Space Institute of Science, USA.

Introduction: One of the problems in astrobiology is how to define and measure the habitability not only of terrestrial environments but also of planetary environments, from the Solar System to extrasolar planets [1]. The word habitability literally means the quality of habitat (the suffix *-ity* means quality, state, or condition). Astrobiologists have been constructing different general definitions of habitability, not necessarily consistent with one another, for some time [e.g., 2,3,4,5,6,7]. Other more specific habitability definitions, such as the canonical Habitable Zone (i.e., presence of surface liquid water on Earth-like planets), are used in exoplanet science [8]. Ecologists have been using since the 1980s the Habitat Suitability Models (HSMs) to study the habitability of Earth from local to global scales; however, this is seldom utilized in the astrobiology community [9].

Here we recommend adapting and expanding the ecologists' nearly four decades of experience modeling habitability on Earth to astrobiology and planetary studies. These models can be used to characterize the spatial and temporal distribution of habitable environments, identify regions of interest in the search for life, and, eventually, explore correlations between habitability and biosignatures. For example, such models would help to test the hypothesis that biosignatures (or biomarkers) are positively correlated with proxy indicators of geologically habitable environments (or geomarkers); i.e., there is life whenever there are habitable environments on Earth.

Measurements by past and future planetary missions can be combined into a standard library of habitability models. Results from different missions can then be compared, even using different measurements, since, through the use of HSMs, their results can be mapped to the same standard scale (e.g., zero for worst and one for best regions). A Habitability Readiness Analysis (HRA) of any mission could be used to determine how its existing instruments could be used, or what sensors should be added, for measurements in the spatial and temporal habitability scales of interest. Furthermore, it might also be possible to develop new sensors for direct habitability measurements.

Recommendations for Planetary Missions: Planetary exploration missions are playing a critical role in our understanding of planetary habitability beyond what remote sensing from space can provide. Planetary exploration mission designs for the upcoming decades may have major astrobiological components that can directly or indirectly inform the study of habitability in the Solar System — even if the determination of habitability is not the primary focus of a mission. Indeed, general mission components not directly designed for astrobiological purposes might usefully contribute to habitability studies with only minimal considerations in design. Here we list four main recommendations for the planetary community:

1. **Increase and widen the participation of more experts on habitat suitability models.** Ecologists are the experts in the ground-truthed proven measurement of terrestrial habitability, yet they are seldom represented in the planetary and astrobiology community. New synergies between NASA and the national and international ecological societies, e.g., the Ecological Society of America (ESA), Soil Ecology Society (SES), and the International Society for Microbial Ecology (ISME), should be established via, for example, a joint conference session at the Lunar and

Planetary Science Conference. There should be worldwide participation to guarantee global standardization. This synergy will stimulate the participation and exploration of the Solar System as a laboratory for expanding our current understanding of the habitability of Earth.

2. **Further terrestrial exploration.** Many Earth habitats are vastly under-explored biologically. For example, the clouds, stratosphere, deep ocean, deep ice, deep earth, or the mantle. Further, astrobiology needs to make stronger connections to the researchers working in these under-studied environments (e.g., The Deep Carbon Observatory) so that there is a cohesive understanding of the state-of-the-art science being learned and efforts to continue to study these environments are supported. These field studies should provide new data to test the applicability of current habitability models with extreme environments, and thus get us closer to diverse planetary conditions. At the same time, unicellular life continually surprises us with new ways to survive and obtain energy from its environment (rock-eaters, electric currents, and even radioactivity) which shows us we need to be flexible in considering energy sources for habitability.

3. **Improve habitability models.** New habitability models should be developed and validated with field and laboratory experiments, including simulated extreme and planetary analog environments. The main goal is to identify knowledge gaps. For example, new ecophysiological response curves (e.g., growth rate as a function of water activity, a measure of available water) for some organisms are necessary, especially in dynamic environments such as gradient-rich biotopes and higher complexity extreme environments (i.e., those with multiple extremes such as deep-sea brines). Also, there are insufficient models on microbial growth in near-surface dynamic environments (e.g., as applicable to martian diurnal cycles). There is a growing body of literature about the manifold mechanisms through which life affects the Earth's climate system, including the global energy balance and atmospheric composition and dynamics. Advances in the understanding of climate-life interactions in the Earth System can provide new insights for habitability models.

4. **Develop a NASA Habitability Standard (NHS)**. Existing and future planetary missions should specify how they assess habitability for each of their instruments according to a shared NASA habitability standard. For example, measurements of surface temperature and water vapor from landers or orbital missions could be converted into a simple habitability model. The advantage of a standard is that past and future missions could be compared to each other and their habitability assessments refined, and new habitability knowledge gaps could be identified. This dynamic standard should be evaluated and updated regularly by a diverse and multidisciplinary committee, for example during a Decadal Survey and/or mid-decade review. Currently, the closest concept to an NHS is specific language included in various NASA roadmaps, such as the NASA Astrobiology Roadmap [10] and the NASA Roadmap to Ocean Worlds [11]. These documents stress the need for habitability evaluations and missions (e.g., Europa Clipper and Titan Dragonfly), yet only focus on the individual habitability requirements and not how to combine the net contribution of these factors. Furthermore, the NHS might eventually become the standard of other disciplines.

Conclusion: NASA should create habitability standards for planetary missions with astrobiology objectives, as the U.S. Fish and Wildlife Service successfully did long ago for ecologists. These standards are necessary to make sense of data from multiple missions, develop predictions for environmental niches on planetary bodies that can be tested, and understand the extraterrestrial correlations between habitability and biosignatures. There is no need for the planetary and astrobiology community to reinvent the habitability methods and tools used by ecologists. The synergy between the methods used by ecologists and astrobiologists will help to integrate and expand our understanding of the habitability of Earth, the Solar System, and extrasolar planets.

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