

THE EVOLUTION OF TERRESTRIAL HABITABILITY. Nicole J. Torres^{1,4}, Joemar Pérez^{1,4}, Jadenys S. Díaz^{2,4}, William J. Molina^{3,4}, and Abel Méndez⁴. ¹Department of Biology, University of Puerto Rico at Arecibo (nicole.torres22@upr.edu). ²Department of Communications, University of Puerto Rico at Arecibo. ³Department of Physics and Chemistry, University of Puerto Rico at Arecibo. ⁴Planetary Habitability Laboratory, University of Puerto Rico at Arecibo, Arecibo, PR, USA (abel.mendez@upr.edu).

Habitability is generally defined as the suitability of environments for life. Photosynthetic primary productivity on Earth is the main supporter of terrestrial life and one of the main indicators of terrestrial habitability (Geider *et al.*, 2001; Milesi *et al.*, 2005; Méndez, 2009). In this study we will use the mass and energy habitability model of Méndez *et al.*, (2018) to trace the evolution of terrestrial habitability from early Earth to climate change. Here we are exploring the main environmental factors to include in our model, including applications to exoplanets.

The use of primary productivity as a measure of habitability is not new. For example, estimates of potential photosynthetic habitable zones (pHZ) on exoplanets have been used to assess the number of habitable planets in the galaxy (von Bloh *et al.*, 2010). Planets around long-lived stars, like M dwarfs, have more time for life to develop, but they also receive less light in the visible range, which might be necessary for photosynthetic life. Certainly, evolution could make exolife better adapted to these conditions, but those cases are harder to compare with geolife because there are many more assumptions to make. As a first approach, it is necessary to establish a terrestrial life baseline for comparison purposes.

Net primary productivity (NPP) is a measure of the organic matter produced by photosynthetic life per unit time and area in land or ocean surfaces. Almost all life, from herbivores to carnivores, depend of this organic matter for survival. For practical reasons, this organic matter is usually measure in grams of carbon, although units of biomass and energy are also used. The mean global NPP of Earth today is about 206 g C m⁻² year⁻¹ (105 Pg C year⁻¹), coincidentally, almost half divided between land and the ocean (Geider *et al.*, 2001).

NPP is determined by many environmental abiotic and biotic factors. Land and ocean NPP is mainly controlled by temperature, light, and atmospheric carbon dioxide. The effect of temperature on NPP is very important at seasonal, and longer scales. Atmospheric opacity, clouds and water turbidity affect light but the solar output is only important at very large time scales in the orders of million years. Carbon dioxide is relevant from centennial and longer time scales. On land, water availability is also a limiting factor and nutrients on the ocean (especially iron and Sulphur). Even biotic

interactions with microbial life controls NPP (Van Der Heijden *et al.*, 2008).

One of the main factor affection terrestrial NPP is temperature. Most terrestrial vegetation are only able to photosynthesize between 0°C to 50°C, with a mean optimum near 25°C for both C3 and C4 plants (higher for C4 plants). This is also true for different biomes where optimum growth temperatures are between 17°C to 29°C (Woodward and Smith, 1994). This is higher than Earth's mean global temperature of 15°C, which forced vegetation closer to the equator and produced clear latitudinal gradients. Consequently, the low latitudes have a higher productivity and support a larger biodiversity, among other explanations (Willig *et al.*, 2003).

Carbon constitutes about 40% of cells dry mass. Primary producers incorporate carbon to their metabolism from atmospheric carbon dioxide. Most of it is extracted during photosynthesis and some is returned back to the atmosphere through respiration. The net effect is some standing biomass with losses due to decomposition and herbivores. The dependence of photosynthesis on carbon follows a Michaelis–Menten model. The minimum CO₂ partial pressures needed for any photosynthesis (C4) is estimated at near 0.01 mbars (10 ppmv) (Percy and Ehleringer, 1984). Growth response at elevated CO₂ quickly saturates beyond 0.45 mbars (450 ppmv) for most plants, with C3 plants being more sensitive than C4 plants (Poorter and Navas, 2003).

Light is the essential ingredient for photosynthesis. Earth's primary producers experience a photon flux density of 1.8 mmol of photons m⁻² s⁻¹ at the surface (Kiang *et al.*, 2007a). Theoretical unicellular light lower limits have been estimated to near 0.1 μmol of photons m⁻² s⁻¹ (Raven, 1984). However, brown sulfur bacteria, living at near 80 m depth in the Black Sea, is adapted to even lower values of 0.003-0.01 μmol of photons m⁻² s⁻¹ (Overmann *et al.*, 1992). The upper limit has been estimated close to 6-9 mmol of photons m⁻² s⁻¹ before photo damage (Wolstencroft and Raven, 2002). Photosynthesis over this saturation conditions is still possible under the protection of haze, cloud cover, water, or ice.

Primary productivity on land and ocean surfaces by plants and phytoplankton, respectively, is not the only

system supporting complex life on Earth, and certainly not the only scenario expected on habitable exoplanets. For example, chemosynthetic bacteria from hydrothermal vents are also known to sustain ecosystems using reduced Sulphur (Cavanaugh *et al.*, 1981; Felbeck, 1981), methane (Childress *et al.*, 1986; Cavanaugh *et al.*, 1987), and more recently hydrogen (Petersen *et al.*, 2011). Also, other more exotic forms of photosynthesis might be possible (Haas, 2010).

Earth's evolutionary history is also an example on how habitable exoplanets could be observed in any stage. The discovery of bacteria fossils from 3,500 Ma (millions of years ago) rocks suggests the presence of Sulphur-metabolizing cells in anoxic environments in the early Earth. Photosynthesis probably started during this time but was only dominant after 2,500 Ma (Anbar *et al.*, 2007). However, it was not after 542 Ma, when oxygen levels were higher and Earth escaped from the last global glaciation, that primary productivity in the surface supported a large and complex diversity on both land and ocean environments. Exoplanets with detectable atmospheric biosignatures but without a discernable biological surface features are possible (Cockell *et al.*, 2009).

According to our habitability model, terrestrial habitability ranged from 0.92 to 1.06 in the last 650 million years. That is, it has changed about 5% during this period. There are two notable periods of greater habitability, one during the Cambrian and the other between the Permian and the Triassic.

Our analysis indicates that in the Cambrian Period the habitability had the largest increase in the time studied. During this period, the Cambrian Explosion occurred, it is the time when most of the major groups of animals first appear in the fossil record. The peaks of habitability coincided with some known events that occurred on Planet Earth. A Pearson Correlations were done to determine patterns and identify possible events associated with changes in habitability. The correlation between habitability and temperature is 0.38, with temperature being one of the parameters that has changed the most over time. The correlation between habitability and oxygen is 0.18, while with the diversity of land animal families it is 0.33, both positive. We also made several Pearson Correlations to estimate the association between paired samples. The habitability and number of insect family have a correlation 0.28. Meanwhile, the habitability and diversity of marine animals of -0.20, which is interesting for the contrast with the families of terrestrial animals.

According to the history of Planet Earth, we know that five major extinctions have occurred. We have

obtained that there is a direct correlation between habitability and the Five Big Extinction with a correlation of 0.4348504.

References:

- Adams, B., White, A., and Lenton, T. (2004). An analysis of some diverse approaches to modelling terrestrial net primary productivity. *Ecological Modelling*, **177**, 3-4, 353-391.
- Geider, R. J., Delucia, E. H., Falkowski, P. G., Finzi, A. C., Grime, J. P., Grace, J., Kana, T. M., La Roche, J., Long, S. P., Osborne, B. A., and others (2001). Primary productivity of planet earth: biological determinants and physical constraints in terrestrial and aquatic habitats. *Global Change Biology*, **7**, 8, 849-882.
- Childress, J. J. *et al.* (1986) A methanotrophic marine mollusc (Bivalvia, Mytilidae) symbiosis: mussels fueled by gas. *Science* **233**, 1306-1308.
- Cavanaugh, C. M., Gardiner, S. L., Jones, M. L., Jannasch, H. W. & Waterbury, J. B. (1981). Prokaryotic cells in the hydrothermal vent tube worm *Riftia pachyptila* Jones: possible chemoautotrophic symbionts. *Science* **213**, 340-342.
- Cavanaugh, C. M., Levering, P. R., Maki, J. S., Mitchell, R. & Lidstrom, M. E. (1987). Symbiosis of methylotrophic bacteria and deep-sea mussels. *Nature* **325**, 346-348.
- Cockell, C. S., Kaltenecker, L., and Raven, J. A. (2009). Cryptic photosynthesis—Extrasolar planetary oxygen without a surface biological signature. *Astrobiology*, **9**, 7, 623-636.
- Felbeck, H. (1981). Chemoautotrophic potential of the hydrothermal vent tube worm, *Riftia pachyptila* Jones (Vestimentifera). *Science* **213**, 336-338.
- Haas, J. R. (2010). The Potential Feasibility of Chlorinic Photosynthesis on Exoplanets. *Astrobiology*, **10**, 9, 953-963.
- Holland HD (1984) *The chemical evolution of the atmosphere and oceans*. Princeton University Press, Princeton, pp 598-608.
- Kasting, J. F. and Howard, M. T. (2006). Atmospheric composition and climate on the early Earth. *Philosophical Transactions of the Royal Society B: Biological Sciences*, **361**, 1474, 1733.
- Kiang, N. Y., Siefert, J., and Blankenship, R. E. (2007a). Spectral signatures of photosynthesis. I. Review of earth organisms. *Astrobiology*, **7**, 1, 222-251.
- Kiang, N. Y., Segura, A., Tinetti, G., Blankenship, R. E., Cohen, M., Siefert, J., Crisp, D., and Meadows, V. S. (2007b). Spectral signatures of photosynthesis. II. Coevolution with other stars and the atmosphere on extrasolar worlds. *Astrobiology*, **7**, 1, 252-274.
- Méndez, A. (2009). Standard Planetary Habitability (SPH) of Global Land Areas on the 40th Lunar and Planetary Science Conference, LPI XXXX #2333.
- Méndez, A., *et al.* (2018). A General Mass-Energy Habitability Model on the 49th Lunar and Planetary Science Conference, LPI XLIX #2511.
- Milesi, C., Hashimoto, H., Running, S. W., and Nemani, R. R. (2005). Climate variability, vegetation productivity and people at risk. *Global and Planetary Change*, **47**, 2-4, 221-231.
- Overmann, J., Cypionka, H., and Pfennig, N. (1992) An extremely low-light-adapted phototrophic sulfur bacterium from the Black Sea. *Limnol. Oceanogr.* **37**(1), 150-155.
- Petersen, J. M., Zielinski, F. U., Pape, T., Seifert, R., Moraru, C., Amann, R., Hourdez, S., Girguis, P. R., Wankel, S. D., Barbe, V., and others (2011). Hydrogen is an energy source for hydrothermal vent symbioses. *Nature*, **476**, 7359, 176-180.
- Anbar, A.; Duan, Y.; Lyons, T.; Arnold, G.; Kendall, B.; Creaser, R.; Kaufman, A.; Gordon, G. *et al.* (2007). A whiff of oxygen before the great oxidation event?. *Science* **317** (5846): 1903-1906.
- Raven, J.A. (1984) A cost-benefit analysis of photon absorption by photosynthetic unicells. *New Phytol.* **98**(4), 593-625.
- Van Der Heijden, M. G. A., Bardgett, R. D., and Van Straalen, N. M. (2008). The unseen majority: soil microbes as drivers of plant diversity and productivity in terrestrial ecosystems. *Ecology Letters*, **11**, 3, 296-310.
- Wacey, D., Kilburn M. R., Saunders M., Cliff J., Brasier M. D. (2011) Microfossils of sulphur-metabolizing cells in 3.4-billion-year-old rocks of Western Australia. *Nature Geosci.* (Advance online publication 2011/08/21).