Mars' near future – Could the surface be made habitable?

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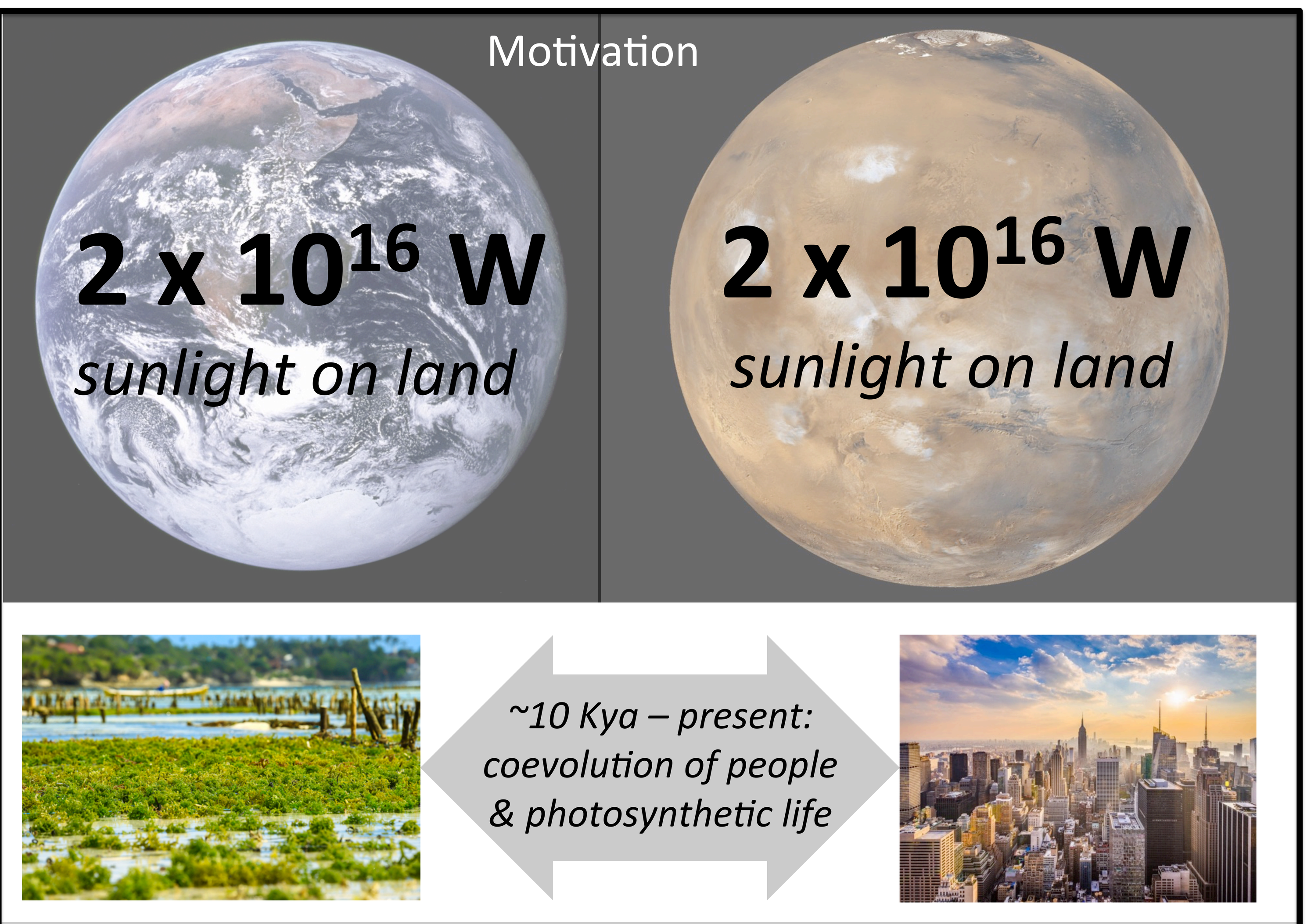
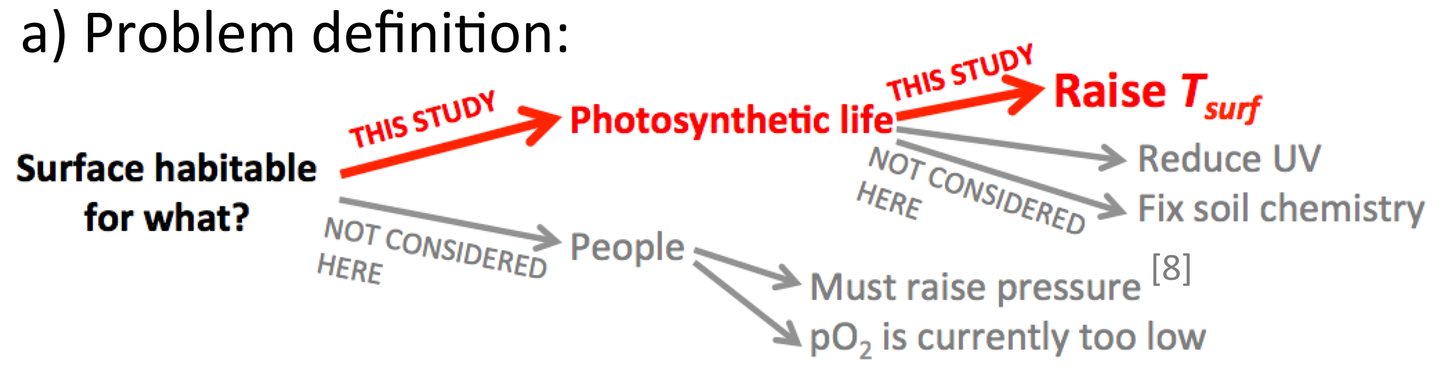
To establish an Earth-derived biosphere on the surface of Mars in future, it is necessary to raise Mars T_{surf}
We consider a new global warming scheme using 5-10 μm-long, <100 nm-diameter metal nanorods.
The resulting warming is near to fundamental physical limits on the efficiency of intentional planet-scale warming.

Motivation



The idea of extending life beyond Earth is as old as science [1-6]. Analyzing Mars warming schemes is intellectually interesting, whether or not we put these schemes into effect. Today Mars receives 40% more energy from the Sun than did Mars 3.5 Gya (when the planet was naturally warm enough to be habitable [7]). Could we get Mars' rivers running again (Fig. 1)?

a) Problem definition:



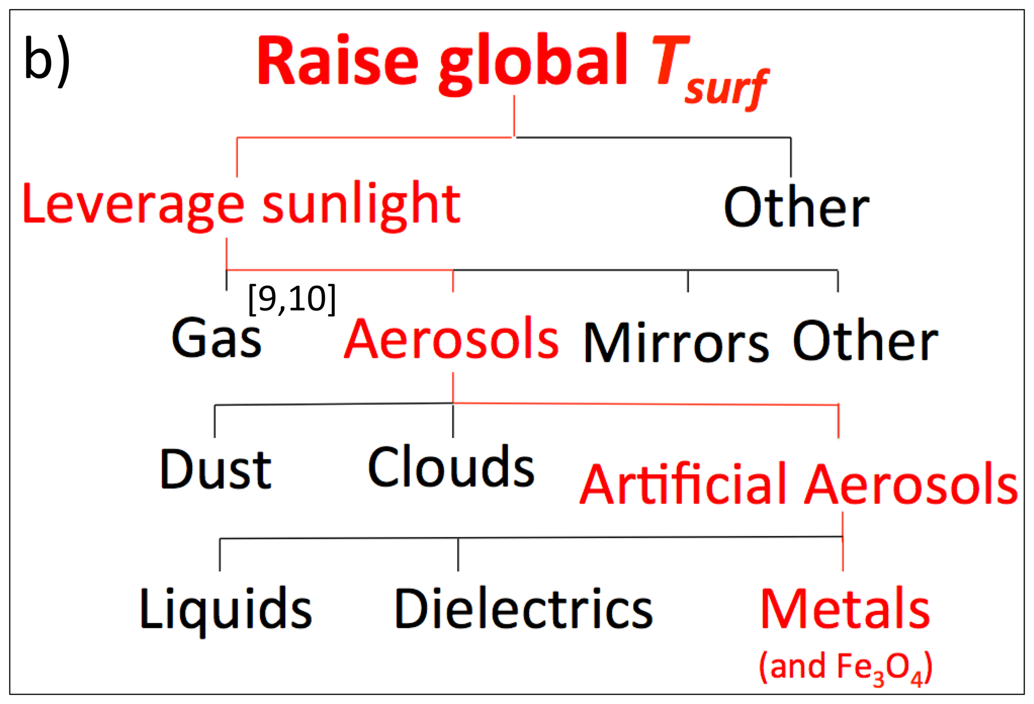


Fig. 1. a) Problem definition. b) Choice of method (red track).

We consider an new global warming agent: metal dipoles (nanoantennae). The method relies only on Mars resources that have been verified in-situ [11]. The method draws inspiration from models of mechanisms to explain 3.5 Gya Mars rivers [e.g., 12-14]. We consider a basic nanoantenna – a ~5-10 μm-long, <100 nm-diameter nanorod. (Real applications would use multiple rod lengths). Rod length is tuned so that extinction efficiency peaks at upwelling thermal-IR wavelengths [15] (Fig. 2). Nanorods settle 10^2-10^3 times more slowly than Mars dust [16], are taken up by dry deposition and by seasonal ice, and are re-released to the atmosphere by sublimation and dust lifting [16-17]. Simplistic calculations (ch. 5 & 12 of [15]) suggest {Fe, Al} nanorod extinction efficiency $Q_a \gtrsim O(10)$ for λ = 10 μm. A figure of merit is the nanorod volumetric injection-to-the-atmosphere rate

$$\dot{V} = \frac{V}{\Delta t} = \frac{\tau\, a}{Q_a\, \Delta t}\left(\frac{V_r}{A_r}\right)$$

where τ is the optical depth needed for strong warming (~5, [12-14]), a is Mars surface area, V_r is rod volume, A_r is rod cross-sectional area, and Δt is nanorod lifetime in the atmosphere.

Scaling for a new warming method:

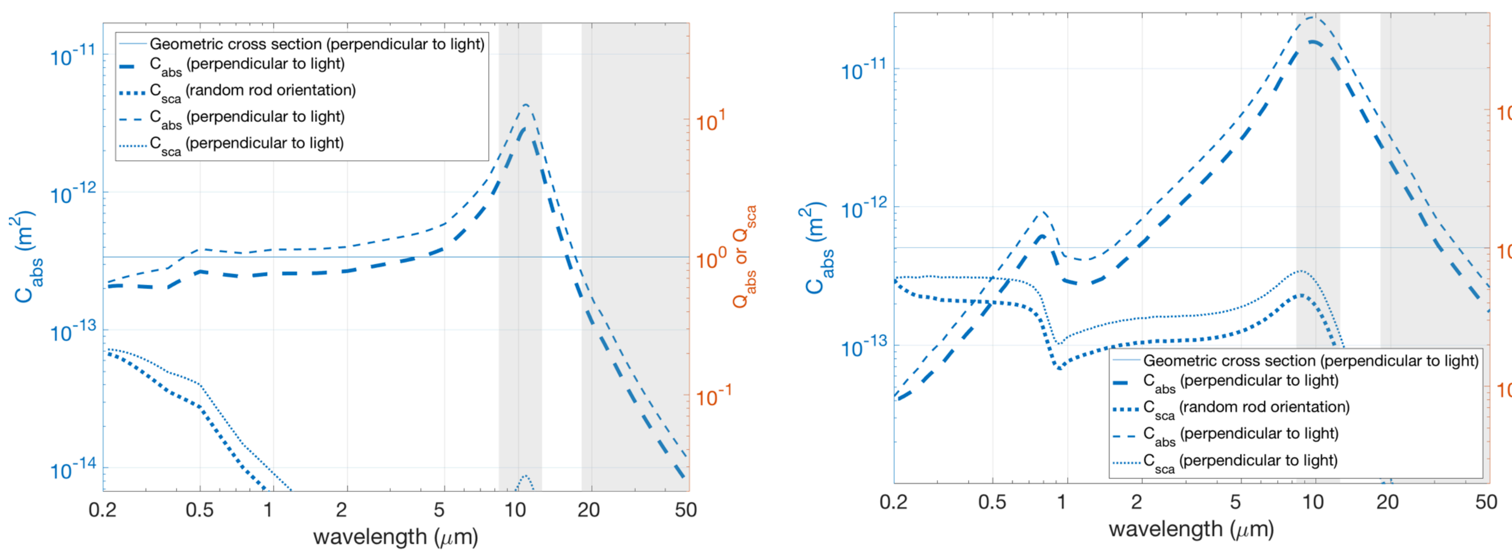


Fig 2. *Left:* Fe nanorods with length and aspect ratio tuned to plug the primary window region (where thermal IR emitted from Mars' surface escapes to space due to poor absorption by CO_2; left gray bar [18]) while forward-scattering most sunlight to the surface. Aspect ratio 90:1. *Right:* As left panel, but for Al nanorods. Aspect ratio 300:1. Peak Q_{abs} exceeds that for Fe. Forward-scattering in the visible.

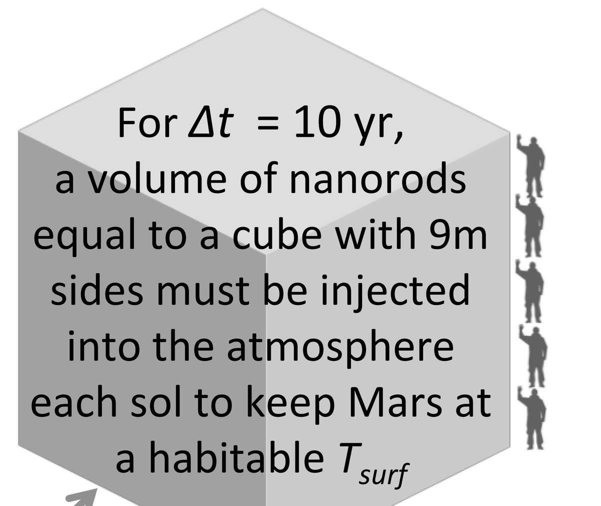
We find

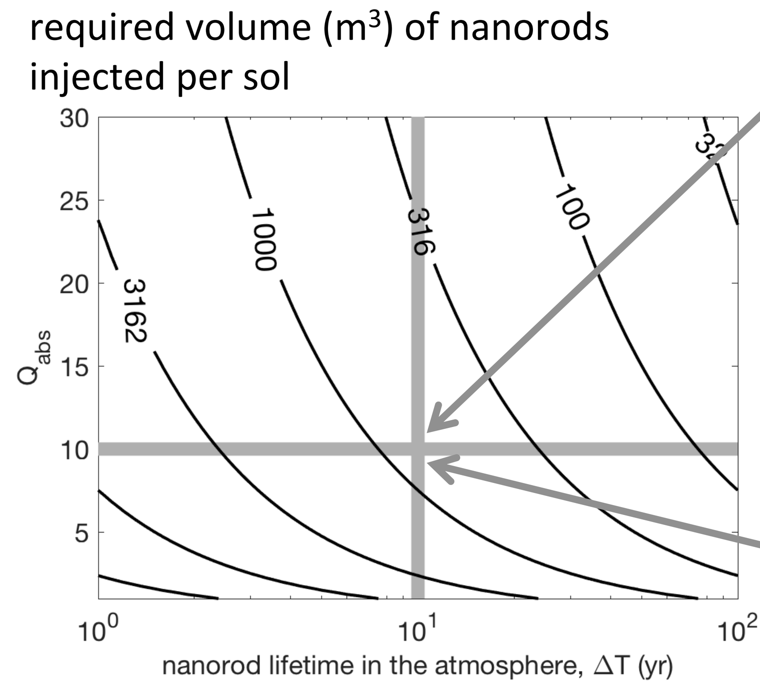
$$\dot{V} = 10^3\,\frac{\mathrm{m}^3}{\mathrm{d}}\left(\frac{10\,\mathrm{yr}}{\Delta t}\right)\left(\frac{10}{Q_a}\right)\left(\frac{r_r}{33\,\mathrm{nm}}\right)$$

i.e. a volume of nanorods equal to a cube with 9-10m sides must be injected into the atmosphere each day to keep Mars at a habitable T_{surf} (Fig. 3).

The spin-up time for steady injection is ~Δt. Δt is the biggest unknown: Δt = 10 yr is slightly optimistic if nanorods do not individually self-loft, but very pessimistic for more sophisticated nanoantennae that might individually self-loft (and also act as sunscreen) [19-20]. If Δt is very long, then the one-shot volumetric injection for τ = 5 corresponds to a volume 0.004 km³. **Winds:** To warm Mars, nanorods must get to high altitude [12,21]. Natural dust distribution caps out at 25 km [17]; by analogy to [12-14], we expect this to be sufficient, although more detailed calculations are needed. Natural dust injection from the surface is by dust devils, gusts, daytime upslope winds, and self-lofting. Nanorods might be injected above the surface layer (e.g., pipe connected to balloon). Nanorods are small enough that (neglecting magnetic effects, e.t.c.) they will collide with the ground before they have a chance to clump together. A key unknown is nanorod reentrainment rate from realistic (dusty, sandy, rocky) surfaces. Zero reentrainment is unlikely; Mars' sky is always dusty. **Nanorod production and injection:** In the Murray formation, $[Fe_2O_3]+[Fe_3O_4]$= (10±5) wt% [e.g., 11]. For a prismatic mine of half-width 225 m bracketing MSL's path, with a side-wall slope of 20°, it is necessary to mine a length of 800 m/yr (for Δt = 10 yr) to obtain Fe-oxide minerals and sustain τ = 5. (A similar mass balance can be done for Al from Al-rich materials at Mawrth; Fe_3O_4 rods are another alternative.) Following metal extraction, thin coatings might be added to slow oxidation. Mineral processing is energy intensive. Falcon Heavy launches (conservatively) 5 t to Mars' surface. Earth seafloor mining robots mass >200 t; mining hardware could be launched in segments. After 3D printing technology is proven in space (e.g. Relativity Space's Stargate metal printer; or last week's selection for flight by NASA of Made in Space, Inc.'s $73 mn Archinaut One spacecraft), then boot-strapping becomes a workable alternative.

Feedbacks under warming. As Mars warms, ice caps release H_2O vapor. This causes: (1) H_2O greenhouse warming (vapor+cloud) [22-24]; (2) increased water-ice scavenging of nanorods. We do not know what effect adding nanorods would have on dust storms. ~6 mbar of CO_2 can be released from South Polar ice caps, and a poorly quantified (but <40 mbar) CO_2 from regolith de-adsorption. So, under warming, atmospheric thickness would increase by a factor of 2-10 (timescale centuries without human intervention). CO_2 release would provide a modest boost in T_{surf}, favor liquid water, and possibly cause H_2O snowfall at low latitudes [25]. Our predictive power is limited for 2-5K of human-induced warming on Earth [26]; although Mars is a simpler system, T_{surf} must rise by ≫5K for a habitable surface. So, it is hard to anticipate how feedbacks will pan out (and therefore, how many nanorods will be needed) on the real Mars.





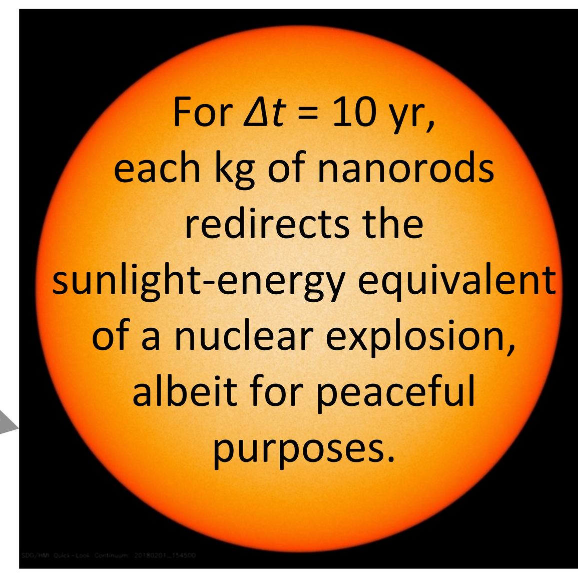


Fig. 3. Required volume injection rate to sustain τ = 5. Gray shows fiducial values.

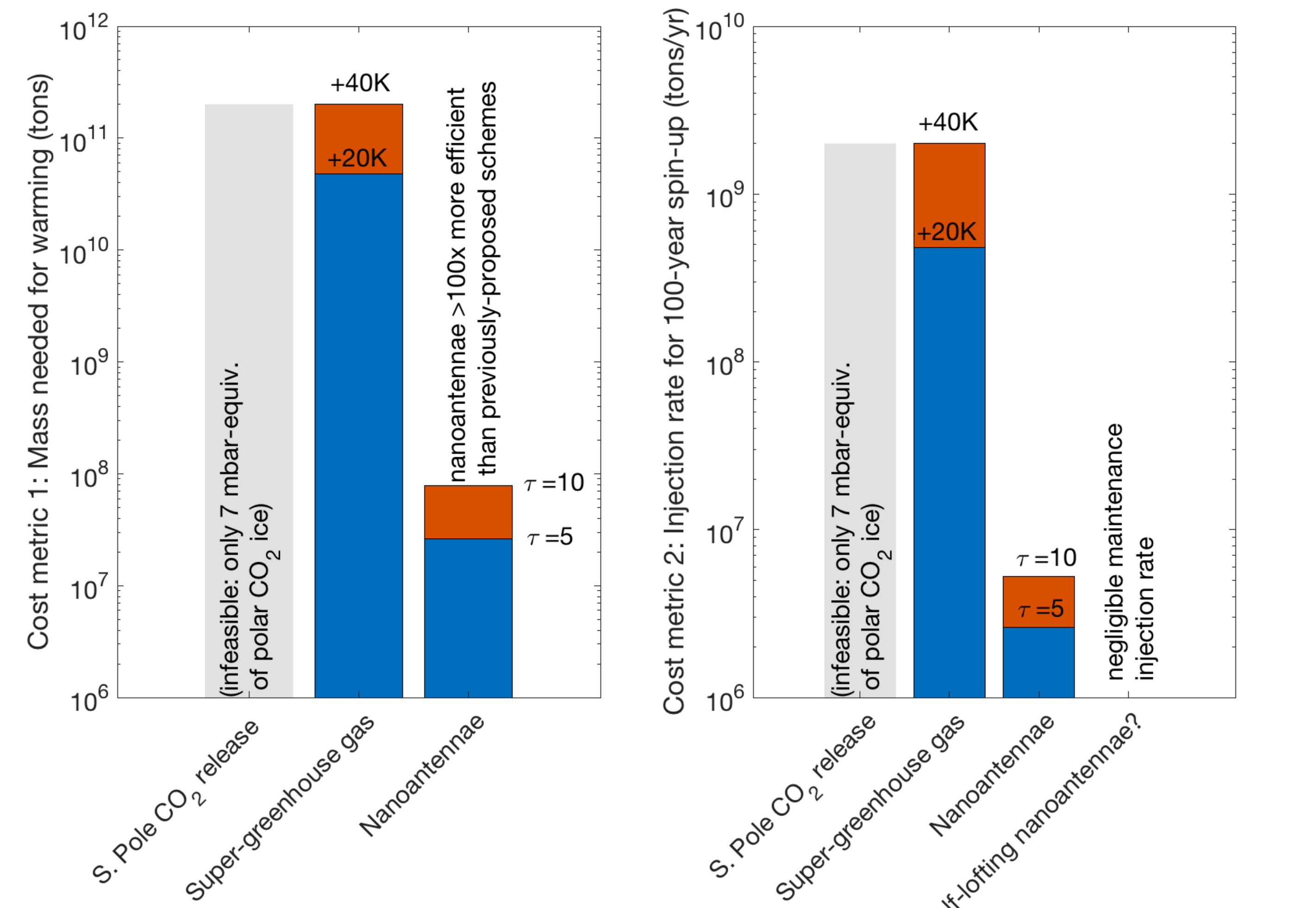
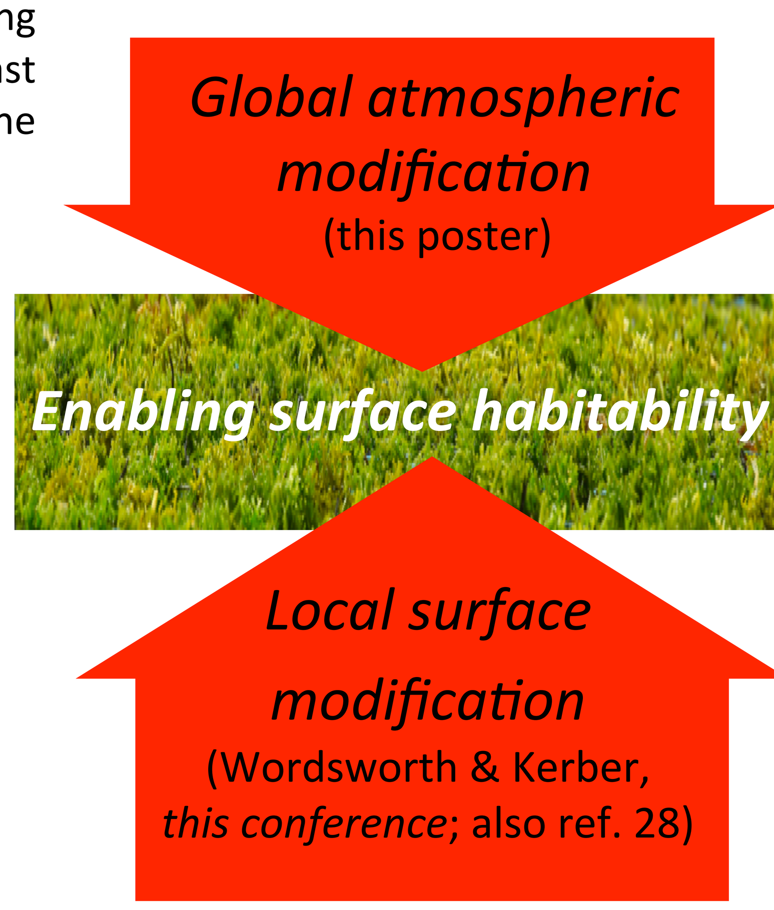


Fig. 4. Cost metrics for Δt = 10 yr, Fe nanorods.

Warming, by itself, is not enough: Mars soil chemistry is problematic. Fortunately, perchlorate-reducing bacteria convert perchlorate to O_2 gas [27]. Global warming can work hand-in-hand with local warming using polymer sheets (± silica aerogel [28]) to minimize evaporitic cooling and water loss and provide physical greenhouse warming for shallow ground ice.



Research needs:

Development of a scheme for intentionally warming Mars engages many sub-fields of current Mars science. Research needs include:- (1) 3D atmospheric modeling of the warm-up. (2) 600 Pa wind-tunnel data for rod reentrainment rate on realistic rough surfaces. (3) Mesoscale modeling of nanorod lofting (passive tracer and self-lofting). (4) End-to-end engineering system modeling. (5) Trial self-lofting experiments starting from surface injection. (6) Tracking of plumes from orbit (cubesats/smallsats) to constrain Δt. (7) Proving of CO_2 ice reserves. (8) Synthetic biology for silica aerogel biomineralization [28].

Raising Mars' temperature, by itself, is not sufficient to make the planet's surface habitable again. Moreover, creating a habitable environment could harm astrobiology research (but might also help it) [28]. Nevertheless, nanoantenna warming is near to fundamental physical limits on the efficiency of intentional planetary warming, and merits attention (alongside other proposed schemes, e.g., [9, 28]) from engineers.

References & resources: [1] Lucretius, *De rerum natura,* book II. [2]. B. de Fontenelle (1686). *Entretiens sur la pluralité des mondes*, the 3rd evening. [3] Bradbury, R., Clarke, A.C., Murray, B., Sagan, C., & Sullivan, W., 1973, *Mars & the Mind of Man*, Harper & Row. [4] Allaby & Lovelock, *The Greening of Mars.* [5] McKay, C., Toon, O.B., & Kasting, J., 1991, *Nature* 352, 489-496 [6] Gerstell, M., et al., 2001, PNAS 98, 2154. [7] Grotzinger, J., et al., 2014, *Science*, 343, 1242777. [8] Jakosky, B., & Edwards, C., *Nat. Astron.* 2, 634-. [9] Marinova, M., et al., 2005, *JGR-Planets* 110, E03002. [10] Dicaire, I. et al., 2013, 3.10x19180, 64th Int. Astron. Congress, Beijing. [11] Hurowitz, J., 2017, *Science*, 356, eaah6849. [12] Ramirez., R., & Kasting, J., 2017, *Icarus* 281, 248-[13] Turbet, M., et al., 2019, arXiv:1902.07666 [14] Mischna, M., et al., this conf. [15] Bohren, C., & D. Huffman, 1983, *Absorption & scattering of light by small particles*. [16] Seinfeld, J., & S. Pandis, 2016, *Atmospheric chemistry and physics*. [17] Haberle, R., et al. (Eds.), 2017, *The Atmosphere and Climate of Mars.* [18] Wordsworth, R., 2016, Annual Reviews of Earth and Planetary Science. [19] Keith, D., *PNAS*, 107, 16428-16431. [20] Lawrence Livermore National Laboratory, 1997, report number UCRL-JC-128715. [21] Pierrehumbert, R., 2010, *Principles of planetary climate*. [22] Urata, R., & Toon, O.B., 2013, *Icarus*, 226, 229-. [23] Madeleine, J.-B., et al., 2014, *GRL.*, 41, 4873-. [24] Kahre et al., this conference. [25] Wordsworth, R., et al., 2015, *JGR-Planets*, 120, 1201-. [26] IPCC, 2014, 5th Assessment Report, Physical Science Basis. [27] Davila, A., et al. *Int. J. Astrobiol.* 12, 321-. [28] Wordsworth et al., 2019, *Nat. Astron.* doi:10.1038/s41550-019-0813-0.