


REVIEW ARTICLE

Extraterrestrial nature reserves (ETNRs)

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Abstract

If human population growth is not controlled, natural areas must be sacrificed. An alternative is to create more habitat, terraforming Mars. However, this requires establishment of essential, ecosystem services on a planet currently unamenable to Terran species. Shorter term, assembling Terran-type ecosystems within contained environments is conceivable if mutually supportive species complements are determined. Accepting this, an assemblage of organisms that might form an early, forest environment is proposed, with rationale for its selection. A case is made for developing a contained facsimile, old growth forest on Mars, providing an oasis, proffering vital ecosystem functions (a forest bubble). It would serve as an extraterrestrial nature reserve (ETNR), psychological refuge and utilitarian botanic garden, supporting species of value to colonists for secondary metabolites (vitamins, flavours, perfumes, medicines, colours and mood enhancers). The design presented includes organisms that might tolerate local environmental variance and be assembled into a novel, bioregenerative forest ecosystem. This would differ from Earthly forests due to potential impact of local abiotic parameters on ecosystem functions, but it is argued that biotic support for space travel and colonization requires such developments. Consideration of the necessary species complement of an ETNR supports a view that it is not humanity alone that is reaching out to space, it is life, with all its diverse capabilities for colonization and establishment. Humans cannot, and will not, explore space alone because they did not evolve in isolation, being shaped over aeons by other species. Space will be travelled by a mutually supportive system of Terran organisms amongst which humans fit, exchanging metabolites and products of photosynthesis as they have always done.

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Introduction

The United Nations (UN) urges protection and restoration of global ecosystems (UN, 2015). However, the human population, predicted to exceed nine billion in 2050 (UN, 2017), requires feeding and c. 37% of the world's land area is used for agriculture (pasture and arable) (FAO, 2017). Some predictions indicate this will increase by 2050 (Öborn *et al.*, 2011); in less than a century, globally significant wilderness may not exist (Watson *et al.*, 2016).

Various estimates put Earth's carrying capacity for *Homo sapiens* at or below eight billion (UN, 2012), so choices are necessary. If human population growth is not controlled, semi-natural areas must be sacrificed to food production and urbanization, engendering ecosystem collapse and environmentally forced population reduction. An alternative is to create more living space, e.g., habitats orbiting Earth or on the Lunar or Martian surface. The concept of extraterrestrial (ET) nature reserves (ETNRs) arises, as envisaged in Douglas Trumbull's 1972 film 'Silent Running'.

Such work is portended by the European Space Agency's (ESA's) MELiSSA project, envisaging closed, bioregenerative life-support for human space missions (e.g., Lasseur *et al.*, 2010), and the contained ecosystems of Biosphere 2 (cf., Nelson, 2018). Plants will be critical to human survival outside Earth (Poulet *et al.*, 2016), as life-support systems, providing food, oxygen (O₂) and water purification (Wolff *et al.*, 2014). Therefore, space exploration requires establishing ecosystem services in ET environments, for pragmatic, selfish and altruistic reasons.

Terraforming Mars is considered (e.g., Sagan, 1973, McKay, 1982, McKay *et al.*, 1991, Birch, 1992, McKay and Marinova, 2001, Beech, 2009, Jakosky and Edwards, 2018, Pazar, 2018). Accepting long time scales, this offers security for Earth life threatened by astronomical or anthropogenic catastrophe. Eventually, Terran-type ecosystems (TTEs) might be assembled on a modified planet's surface, though contained communities may be achievable sooner and as a necessary step.

Mars is therefore proposed as a location for a contained TTE (CTTE). Assuming containment can provide tolerable conditions, Mars offers gravity, atmosphere, sufficient sunlight for photosynthesis (Table 1) and water (Rummel *et al.*, 2014), while proximity to Earth allows management.

A Martian CTTE would self-justify, offering refuge, retreat and ecosystem services for astronauts concerned with exploration, resource harvesting or colonization. It would provide wonder, inspiration, purpose and a psychological stepping-stone for more ambitious projects. Humanity's exploration of space will need a network of such oases, supporting terraforming resources and offering biotic refreshment. Forest ecosystems would be apposite.

Forest environments have health benefits (stress reduction, recovery from fatigue, rehabilitation) (Karjalainen *et al.*, 2009). Ancient forests have emotional, spiritual and cultural significance (e.g., Lowman and Sinu, 2017). Threatened by human impact (Frank *et al.*, 2009; Laurance, 2015), they are archetypes, visions of arboreal majesty and biotic complexity (e.g., Wirth *et al.*, 2009). Such TTEs would offer relief from ET sterility.

Facsimile old growth forest could be established over a century on Earth (Smith, 2018), but present-day Mars' surface is hostile to Earth-adapted life, with high radiation levels (Nixon *et al.*, 2013), thin atmosphere and other stressors (e.g., Table 1). TTEs would need shielding.

This account assumes a semi-autonomous, contained environment could be created on Mars, large, strong and shielded enough to support a forest, hold positive atmospheric pressure, protect it from meteorites (e.g., Daubar *et al.*, 2019) and exclude harmful radiation (a 'forest bubble', McKay 2022 personal communication 20th August) (Fig. 1).

Challenges of constructing, large Martian 'worldhouses' have been discussed (Taylor, 1992; 1998). Acknowledging small containments' limitations (Taylor, 1998), and flaws in minimum habitat areas

Table 1. *Relative characteristics of Earth and Mars*

	Earth	Mars
Surface gravity (Manzano <i>et al.</i> , 2018)	1 g (9.81 m/s ²)	0.38 g (cf. Earth's Moon 0.17 g)
Geomagnetic field	<30 to >60 μ T at surface (Occhipinti <i>et al.</i> , 2014)	Local, crustal magnetic fields (Acuña <i>et al.</i> , 2001)
Solar irradiance (W/m ²) (Williams, 2021a)	1361.0	586.2
Relative day length (Williams, 2021a)	1	1.03
Year length (McKay and Marinova, 2001)	365.25 days	687 days
Sunlight relative to Earth	100%	43% (McKay <i>et al.</i> , 1991). Sufficient for photosynthesis (Lehto <i>et al.</i> , 2006; Cockell and Raven, 2004; Verseux <i>et al.</i> , 2016)
Ultraviolet light (UV) (McKay and Marinova, 2001)	>300 nm	>190 nm
Average temperature (mean temperature of body over entire surface)	288 K (15°C) (Williams, 2021b)	c. 210 K (– 63°C) (Williams, 2021a)
Temperature range (McKay and Marinova, 2001)	–60 to 50°C	–145 to 20°C (to c. 35°C, NASA, 2007)
Surface atmospheric pressure	101 400 pascals (1014 mbar) (Williams, 2021b)	636 pascals (6.36 mbar) (Williams, 2021a) (potentially 12.4 mbar seasonally in Hellas basin (Haberle <i>et al.</i> , 2001)
Atmospheric oxygen (O ₂)	20.95% (Williams, 2021b)	0.16% (Williams, 2021a)
Atmospheric carbon dioxide (CO ₂)	Minor component (415 ppm) (Williams, 2021b)	95.1% (Williams, 2021a)
Atmospheric nitrogen (N ₂)	78.08% (Williams, 2021b)	2.59% (Williams, 2021a)
Atmospheric argon (Ar)	Minor component (9340 ppm) (Williams, 2021b)	1.94% (Williams, 2021a)

Residual atmospheric composition (ppm) (CO as %)	H ₂ O (c. 1%); H ₂ 0.55; CH ₄ , 1.7; He 5.24; Kr 1.14; Ne 18.18 (Williams, 2021b)	H ₂ O 210; NO 100; Hydrogen-deuterium-oxygen 0.85; Kr 0.3; Ne 2.5; Xe 0.08; (CO 0.06%) (Williams, 2021a)
Surface UV flux (W/m ²) (average levels at zenith angle of 0° (after Cockell and Andradý, 1999))	UVC (200–280 nm) c. 0	4.1 (at perihelion ¹)
	UVB (280–315 nm)	2.0
	UVA (315–400 nm)	56.8
		9.6 (at perihelion ¹) 37.9 (at perihelion ¹)

¹Perihelion: closest point to sun during an elliptical orbit, therefore maximum incident UV flux.

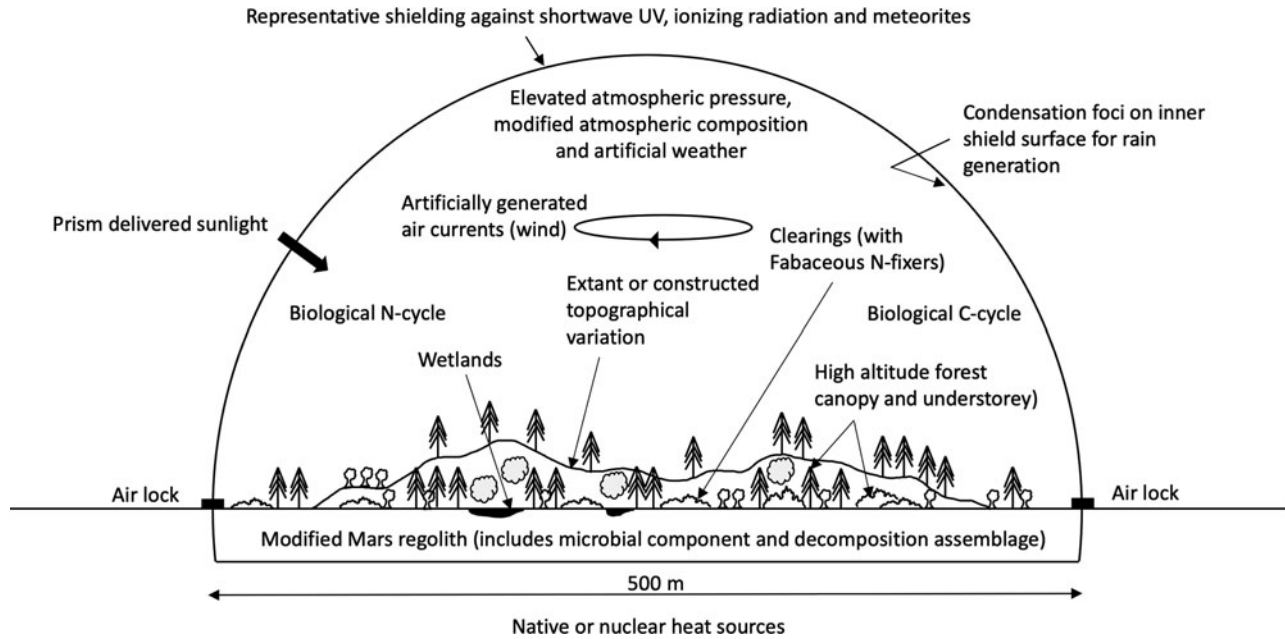


Fig. 1. Conceptual drawing of 20 ha footprint 'forest bubble' (location may constrain shape).

(e.g., van der Hoek *et al.*, 2015), a hemispherical, environmentally controlled, enclosure of c. 0.25 km radius is envisaged (20 ha footprint). Many semi-natural Earth woods are smaller (e.g., Peterken, 1993) and Biosphere 2's designed rainforest occupies c. 0.2 ha (Nelson, 2018).

Outlining of constraints (cf. Table 1) leads to justification of a concomitant forest design with novel species complement (cf. Table 2). Discussion of ethics follows.

Environmental constraints

Ionizing particle radiation (IR)

Unlike Earth, Mars lacks a significant global magnetic field to exclude incoming charged particle radiation (e.g., Atri, 2016), its surface subject to solar energetic particles and galactic cosmic radiation that damage living tissues (e.g., Nelson, 2013, 2016).

Artificially generated magnetic (e.g., Townsend, 2005; Battiston *et al.*, 2012; Bamford *et al.*, 2014; Ambroglini *et al.*, 2016), or electrostatic (Tripathi *et al.*, 2008; Joshi *et al.*, 2013) fields, improved passive shielding, local crustal magnetic fields (e.g., Alves and Baptista, 2004) and/or thick layers of Mars regolith (e.g., Röstel *et al.*, 2020) might provide solutions.

Dohm *et al.* (2011) consider cavern refuges. One existing skylight accesses a void at least 37 m deep (Cushing, 2012). Such places might protect CTTEs from IR. Prisms could refract sunlight into underground chambers (cf. Luxfer prisms, Neumann, 1995), IR bypassing them.

Sunlight (including UV)

Martian day length resembles Earth days, and CTTEs can exploit local sunlight (Table 1). Subterranean situations might use mirror/fibre optic delivery, augmented by light emitting diodes (Nakamura *et al.*, 2013). Electric light requires maintenance but sunlight collection is vulnerable to dust storms (e.g., Fernández, 1998; Martínez *et al.*, 2017). Self-cleaning, light-harvesting surfaces are needed. Superomniphobic materials (Sun and Böhringer, 2019) augmented by electrodynamic technology (Mazumder *et al.*, 2016) or 'plasma brooms' (Ticoş *et al.*, 2017) might provide solutions but surface micro-/nano-coatings are short-lived (Sun and Böhringer, 2019). Vertical light-harvesting surfaces might shed dust, while light-transmitting plants (e.g., Duckett and Ligrone, 2006) might inspire materials.

Besides diffuse illumination, forest understoreys experience sunflecks (short periods of direct irradiance when sun penetrates canopies) (e.g., Pallardy, 2008). Their nature depends on canopy physiognomy, solar declination and solar time (Chazdon and Pearcy, 1991). Sunflecks are energy sources, significant to small organisms (including seedlings) and potential stressors (e.g., Leakey *et al.*, 2004). Photosynthesis during them may provide 30–60% of daily C gain (Chazdon, 1988), plants' responses involving UVB photoreceptors (Moriconi *et al.*, 2018).

Static, unidirectional lighting in windless CTTEs would not engender sunflecks' dynamic chiaroscuros (cf. Way and Pearcy, 2012), so lighting manipulation, exposure to natural solar ecliptic and/or leaf-animating wind is needed.

Mars' harsh surface UV flux (Table 1) is sterilizing due to thin atmosphere and lack of significant ozone (Cockell *et al.*, 2000; Kminek *et al.*, 2010). UV has positive (Juzeniene and Moan, 2012) and negative (e.g., Lee *et al.*, 2013, Rettberg *et al.*, 2004) effects on organisms. Fortunately glass/plastic combinations can exclude harmful wavelengths whilst transmitting beneficial UV and visible light (e.g. Duarte *et al.*, 2009; Tuchinda *et al.*, 2006), so flux in CTTEs can be controlled.

Some UV is necessary for vitamin D synthesis and other mechanisms in animals (e.g., Juzeniene and Moan, 2012; Wilson *et al.*, 2012; Baines *et al.*, 2016) and necessary irradiances may be determined (Cockell and Andrady, 1999). Many, non-human animals have vision in the UV spectrum (e.g., Bennett and Cuthill, 1994, Cronin and Bok, 2016) including honeybees (*Apis mellifera*) (Reverté *et al.*, 2016). Some pollinators use UVA for navigation (Cockell and Andrady, 1999). Human wellbeing and ecosystem function will therefore require modulation, not total exclusion, of Mars' UV flux.

Magnetic fields (MFs)

Life evolved within Earth's geomagnetic field (GMF) (Maffei, 2014). Magnetic guidance mechanisms exist in some microorganisms, and many animals (Frankel, 1984) and MF changes might impact plant growth and development (Wolff *et al.*, 2014). So, some behaviours might be compromised on Mars due to the lack of a GMF. This may affect CTTEs.

Climate, temperature and pressure

Mars' mean surface temperature is -63°C . While periods above freezing occur, surface atmospheric pressure is so low (Table 1), any water ice that melts usually sublimates to vapour (Lewis, 2003). The limit for higher plant tissue growth may be 5°C , little occurring at $6-7^{\circ}\text{C}$ (Körner, 2008). 'Biologic zero' relates to soil temperatures when microorganisms and or plants become inactive, sometimes considered 5°C (Rabenhorst, 2005). CTTEs must therefore maintain elevated internal air temperature and pressure.

Mars' equator might offer a thermal advantage over other Areal locations for a CTTE. However, other factors apply. Haberle *et al.* (2001) discussed regions where ground temperature and surface pressure can be favourable for the existence of liquid water, including the Hellas basin. The base of this 9 km deep impact crater (Ali and Shieh, 2014) potentially experiences 12.4 mbar surface pressure during the northern summer (Haberle *et al.*, 2001). Such locations might facilitate contained pressure differentials.

CTTEs will require heating and dispersal of excess heat. Inevitably, heat will be lost to the external environment over time. No insulation is perfect, seals must allow ingress/egress, and dust storms (cf. Fernández, 1998) will reduce solar benefits but 'intelligent' computer-controlled structures (Taylor, 1998) might maintain suitable environments. Biosphere 2's complex control systems indicate engineering challenges and power needs (Nelson, 2018).

Solar power has potential (e.g., Delgado-Bonal *et al.*, 2016; Vicente-Retorcillo *et al.*, 2018) but due to dust storms (Fernández, 1998), hybrid power generation, with rechargeable batteries and/or nuclear thermoelectric technology (e.g., LaMonica, 2012; NASA, 2019a), may be needed. Geothermal options might exist (Morgan, 2009; Sori and Bramson, 2019).

Seasons

Biomes change seasonally, so CTTEs require seasons. Temporality determines critical developmental stages, individual physiologies and interspecific relationships, while timing of abiotic events influences global nutrient fluxes (Forrest and Miller-Rushing, 2010). Photoperiod and winter chilling are involved in temperate plants' phenology (Richardson *et al.*, 2013). Development of many insects is seasonally synchronized, enabling tolerance of adversity (Danks, 2007). Phenological cycles are fundamental to ecosystem function (e.g., Stucky *et al.*, 2018) and climate changes can desynchronize critical interactions (Thackeray *et al.*, 2016). Seasons also imbue characteristics critical to psychological restoration, e.g., autumn colour, winter silence, spring flowers and summer leafiness.

Mars has four seasons, approximately twice duration of Earth's (e.g., ESA, 2019). These vary in length due to its elliptical orbit, spring in the northern hemisphere (autumn in the southern) being the longest (NASA, 2019b). Whether Earth organisms can adapt to Mars seasons, even in containment is unknown.

Conditions on Earth have not selected for tolerance of seasons of such asymmetry and length (Taylor, 1998). So, CTTEs need artificially controlled seasons (diverging from semi-autonomy) or to be assembled from species tolerant of seasonal aberrance, the latter if relying heavily on passive sunlight delivery.

Lunar cycle

Most Earth organisms have circadian clocks, endogenous, molecular timing systems, allowing anticipation of Earth's 24-h light-dark cycle and maintenance of behavioural cycles (Bollinger and Schibler,

Table 2. Potential integrants for contained Martian TTE

Forest element	Taxon	Justification	Ecosystem services
Canopy layer Forest structure. Building materials, fibres, paper, fuel, food, medicines (e.g., FAO, 2014).	<i>Alnus glutinosa</i> (Betulaceae)	Monoecious tree of wet soils, reproducing by seed (McVean, 1953). Symbiotic, N-fixing actinomycete <i>Frankia</i> in roots (Dawson <i>et al.</i> , 2005). Actinorhizal plants provide major N source in terrestrial ecosystems (Dawson, 1986). Schimel <i>et al.</i> (1998) indicate importance in early successional boreal forest, contributing N and C to developing soils and facilitating establishment of soil N-cycle . Exhibits chlorosis on calcareous soils and intolerant of 6 months mean daily temperature $\leq 0^{\circ}\text{C}$ but seed germination independent of substrate pH (3.5–8.0).	Nitrogen fixation. Tanniferous wood resistant to decay in water (McVean, 1953).
	<i>Acer saccharum</i> and <i>Acer spicatum</i> (Sapindaceae)	<i>A. saccharum</i> : keystone species in North American/Canadian forests important for birds and invertebrates (Minorsky, 2003). Withstands cold winters (USDA Hardiness Zones 3–8 (–34.4 to –6.7°C)) (Missouri Botanical Garden, 2022a). <i>A. spicatum</i> : survives average annual extreme minimal temperatures of –40 to –45.6°C (USDA Hardiness Zone 2) (see Miller, 2006).	Aesthetics , seasonal colour, dynamism, low gravity leaf/fruit fall (winged samaras). Sugary sap (syrup) (Minorsky, 2003).
	<i>Betula</i> species (Betulaceae)	Long-lived pioneer species of successional environments. Atkinson (1992) reviews. <i>B. pendula</i> can live to 180 years (Mitchell, 1974). <i>B. pubescens</i> ssp. <i>tortuosa</i> forms treeline at c. 700 m a.s.l. in Sweden (Truong <i>et al.</i> , 2007). <i>Betula</i> spp. grow on nutrient-poor soils and have a wide geographical and edaphic range while ectomycorrhizal associates sometimes increase zinc tolerance (Atkinson, 1992). Extent into Siberia corresponds to c. mean January temperature of –30°C for <i>B. pubescens</i> , –20°C for <i>B. pendula</i> (Atkinson, 1992, referencing Meteorological Office 1978 data). Many associated insects (e.g., Kennedy and Southwood, 1984). Being monoecious (Simpson, 2010), managed airflow and anemophily obviate need for pollinating insects.	Food, alcohol and fuel. Pharmaceutical, cosmetic and dietary applications (Krasutsky, 2006). Essential oils for flavouring and medicine (Demirci <i>et al.</i> (2004)). Antimicrobial potential of associate <i>Fomitopsis betulina</i> (Pleszczyńska <i>et al.</i> , 2017). Winged seeds contribute dynamism .
<i>Cupressus gigantea</i> (Cupressaceae) (potentially a variety of <i>C. torulosa</i> (Maerki and Hoch, 2013))	Imposing canopy trees. Native to altitudes >3000 m a.s.l. and considered endangered (Maerki and Hoch, 2013). Suitable for USDA Hardiness Zone 7 (Trees and Shrubs online, 2020), i.e., tolerates annual extreme minimum temperature of –17.8 to –12.2°C (USDA, 2012). Reaching 40 m tall, some groves protected as ‘sacred forest’ (Farjon, 2010).	Building wood, scented volatiles , wood-preserving terpenes and incense (Farjon, 2013). Potential height offers a sense of wonder and incites pilgrimage .	

(Continued)

Table 2. (Continued.)

Forest element	Taxon	Justification	Ecosystem services
	Ericaceae	Heavy metal tolerance for iron-rich Martian regolith. Ericaceous plants dominate nutrient poor, acidic soils with high levels of potentially toxic metals. This is attributed to ericoid mycorrhizal fungi (Daghino <i>et al.</i> , 2016). These capture N and P and limit plant's accumulation of metals (see Bradley <i>et al.</i> , 1982). <i>E. trimera</i> is a high-altitude canopy species (Hemp, 2006).	Heavy metal tolerance (see also shrub layer).
	<i>Juniperus tibetica</i> , <i>J. convallium</i> (Cupressaceae)	Longevity offers continuity, opportunity for legacy. Many oldest recorded trees are conifers (Rocky Mountain Tree-Ring Research, undated); drought stress resistance due to xylem structure (Patten <i>et al.</i> , 2010, Choat <i>et al.</i> , 2012) might contribute to longevity (FAO, 2014). Junipers are long-lived (Ward, 1982, Liang <i>et al.</i> , 2012, Rocky Mountain Tree-Ring Research, undated, Liu <i>et al.</i> , 2019). <i>J. tibetica</i> is a high-altitude treeline species tolerant of extremes of solar radiation and frost (e.g., Farjon, 2010). Often grows with <i>J. convallium</i> (Miehe <i>et al.</i> , 2003). Juniper seeds' adaptation for dispersal by frugivores (Chambers <i>et al.</i> , 1999) necessitates artificial seed dispersal if co-evolved animal vectors are excluded.	Bazin (2013) notes sacred status of high-altitude juniper, forests (' incense forests ') in Tibetan Buddhism providing aromatics and defining sacred spaces. Invokes connection and pilgrimage.
	<i>Lagarostrobos franklinii</i> (Podocarpaceae)	Longevity. Tasmanian species, sea level to 1000 m a.s.l. and hardy to USDA Zone 8 (down to -12.1°C) (Christian, 2022). Forms long-lived clonal colonies. Ring counts indicate tree ages >2500 years, pollen analysis indicates a clone >10 000 years old (see Earle, 2020). Endangered by over exploitation (Fitzgerald and Line, 1990).	Longevity. Methyl-eugenol in timber confers resistance to decay (Fitzgerald and Line, 1990).
	<i>Picea abies</i>	Tolerant of shade, dry and wet habitats , monoecious, and dominates north European boreal forests, reaching 2300 m a.s.l. (Skrøppa, 2003). One individual 9550 years old (Umeå University, 2008). USDA Hardiness Zones 2–7 (i.e., to -45.6°C) (Missouri Botanical Garden, 2022d). Anemochorous, numerous mycorrhizal associates and preference for acidic soils (Caudullo <i>et al.</i> , 2016).	Wood for musical instruments (Caudullo <i>et al.</i> , 2016) and fibres for paper (Skrøppa, 2003). Resin found in propolis honeybees use to control hive pathogens (Drescher <i>et al.</i> , 2019). Potential for art and music, link with Earth.
	<i>Pinus sylvestris</i>	Dominates climax vegetation on many nutrient-deficient sites , planted on wide ranging soil types and tolerating severe cold to Mediterranean climates (Carlisle and Brown, 1968). Supports	Competitiveness. Resin found in propolis (Drescher <i>et al.</i> , 2019).

Shrub layer

Diversifies niches and products.
Enhances human experience.

<i>Populus</i> species	<p>diverse bryophytes, lichens (Øyen <i>et al.</i>, 2006) and arthropods (Thunes <i>et al.</i>, 2004).</p> <p>Genus may have potential for perchlorate degradation either directly (van Aken and Schnoor, 2002) or by root products driving bacterial perchlorate respiration (Shrout <i>et al.</i>, 2006). <i>P. tremuloides</i> resisted freezing to – 80°C and survived immersion in liquid nitrogen (– 196°C) (Sakai and Weiser 1973). Has potential to form extensive clonal colonies (DeWoody <i>et al.</i>, 2008).</p> <p>Successions of <i>Salix</i>, <i>Equisetum</i>, <i>Alnus</i> and <i>Populus</i> facilitate development of soil nutrient cycles (Schimel <i>et al.</i>, 1998). <i>Populus</i> ecosystems support diverse species (Rogers and McAvoy, 2018).</p> <p>Dioecious (Byng, 2014) so both genders needed for fertile seed but anemophily (Meikle, 1984) allows pollination by air.</p>	<p>Potential for perchlorate degradation. Fast-growing, low-flammable timber (Mabberley, 1987) Resin of <i>P. balsamifera</i>, <i>P. × canadensis</i> found in propolis (Drescher <i>et al.</i>, 2019). Resin provides seasonal perfume.</p>
<i>Salix</i> species	<p>Possible potential for perchlorate uptake and remediation (Susarla <i>et al.</i>, 2000). Twigs and buds of some species survive liquid nitrogen immersion if winter-hardened (Stushnoff and Junttila 1986). Even some tropical species show a high degree of freezing resistance (Sakai, 1970). Many associated insects (e.g., Kennedy and Southwood, 1984).</p> <p>Predominantly dioecious, examples pollinated by wind and insects (e.g., Tollsten and Knudsen, 1992). Both genders needed.</p>	<p>Potential for perchlorate remediation. Analgesic. <i>Salix</i> provides precursor to acetylsalicylic acid traded as aspirin (e.g., Mahdi <i>et al.</i>, 2006).</p>
<i>Caragana</i> species	<p><i>C. versicolor</i> is a keystone leguminous, Himalayan shrub; cushion-like form and thick rootstock adapt it to cold aridity at 3800–5400 m a.s.l. (Kumar <i>et al.</i>, 2016). Grazed by animals, it helps maintain the Trans-Himalayan ecosystem (ibid.).</p> <p><i>C. arborescens</i>, hardy down to USDA Hardiness Zone 2 (Reza, 2015) (– 45.6 to – 40°C average annual extreme minimum temperature). Potential in mine spoil reclamation (e.g., Hensley and Carpenter, 1986). Shortt and Vamosi (2012) review its tolerance, including alkaline and saline soils. It invades forest understorey (Henderson and Chapman, 2006).</p>	<p>N-fixation and salinity tolerance. Potential for forest edge or open conifer woodland.</p>

(Continued)

Table 2. (Continued.)

Forest element	Taxon	Justification	Ecosystem services
	<i>Eleagnus angustifolia</i>	Fast-growing temperate Eurasian tree of mountains, plains and desert (CABI, 2019). Extending to cold, high altitude, Trans-Himalayan regions (Singh <i>et al.</i> , 2008) and surviving frosts of –30°C (Bartha and Csiszár, 2008). Katz and Shafroth (2003) review its invasiveness in riparian environments indicating actinorhizal N-fixation, tolerance of alkalinity and salt , xerophytic capacity, seeds with three-year dormancy. With hermaphrodite flowers (Singh <i>et al.</i> , 2008), it establishes from seed, and mycorrhizal inoculum is available (CABI, 2019).	Fragrant , insect-pollinated flowers (Katz and Shafroth, 2003). Attractive wood with artisan potential (Vaughan and Mackes, 2016). Edible fruit high in vitamin C and nectar used by bees to make honey (Bartha and Csiszár, 2008). Terrestrial halophytes may include colonists tolerant of Mars salty regolith.
	<i>Tamarix ramosissima</i>	<i>T. ramosissima</i> – <i>T. chinensis</i> hybrid complex highly invasive in arid-climate riparian zones (Global Invasive Species Database, 2015). Killed by temperatures below –33°C (within temperature range of the North American Great Plains) (Friedman <i>et al.</i> , 2008) but this shows some resilience to cold. Seeds have no dormancy and germinate immediately (Global Invasive Species Database, 2015). A facultative phreatophyte able to switch between groundwater and unsaturated soil moisture, it invades xeric and saline riparian habitats (Sun <i>et al.</i> , 2016), excreting excess salt through leaf glands (Global Invasive Species Database, 2015). Will grow in perchlorate contaminated ecosystems (Urbansky <i>et al.</i> , 2000).	Salt (and some perchlorate) tolerance. Provides nectar and a useful wood (Global Invasive Species Database, 2015).
	<i>Fallopia (Reynoutria) japonica</i>	Invasive by vegetative spread, growing on various soil types including colliery spoil, clays and free-draining mineral soils, at pHs of 3.0–8.5 (Beerling <i>et al.</i> , 1994). Shows tolerance to heavy metals (Michalet <i>et al.</i> , 2017) and salt (Rouifed <i>et al.</i> , 2012). <i>F. japonica</i> colonizes volcanic soils including basaltic gravels with poor nutrient and water-holding capacity (Beerling <i>et al.</i> , 1994). Range extends to 3800 m a.s.l. (CABI, 2020). Though vulnerable to frost (Beerling <i>et al.</i> , 1994), distributional and climate data indicate geographical extent is limited by minimum temperatures of –30.2°C (Beerling, 1993).	<i>F. japonica</i> and <i>F. sachalinensis</i> provide most of the resveratrol (anticancer drug) in nutritional supplements (CABI, 2020). Heavy metal tolerance.

<i>Pueraria</i> spp.	<p>Problematic on Earth, due to invasiveness, fast-growing kudzu vine (various <i>Pueria</i> spp.) (Fabaceae) might provide a forest climber. Well-known invasive ability (e.g., Harron <i>et al.</i>, 2020) but isoprene emission and high N-fixation capacity (doubling soil NO fluxes) make <i>P. montana</i> a unique source of tropospheric ozone precursors (Hickman <i>et al.</i>, 2010). This is a pollution concern on Earth but highly beneficial for Mars terraforming. Coiner <i>et al.</i> (2018) indicate <i>P. montana</i> var. <i>lobata</i> can acclimatize to cold, potentially surviving down to -26°C. <i>Pueria</i> spp. are problematic on legacy mine sites, interfering with reforestation (Burger <i>et al.</i>, 2013), but <i>P. montana</i> var. <i>lobata</i> is also a lead hyperaccumulator, considered for phytoremediation (Schwarzauer-Rockett <i>et al.</i>, 2013).</p>	<p>Ozone formation, N-cycle, fast-growing.</p>
<i>Hippophae rhamnoides</i>	<p>Deciduous, dioecious shrub of mountain riversides, sandy gravel (Gutzeit <i>et al.</i>, 2008) and sand dunes (Pearson and Rogers, 1962). Seeds viable after 12 weeks at -20°C and require low temperature before germination (<i>ibid.</i>, 1962). Tolerates temperatures of -45 to $+43^{\circ}\text{C}$ (Krejcarová <i>et al.</i>, 2015). Cold resistant, drought-tolerant and saline-alkali resistant, will grow at 60–5200 m a.s.l. and is distributed over arid/semi-arid high mountain ecosystems of Eurasia (Husain <i>et al.</i>, 2018). <i>Frankia</i> symbionts allow N-fixation and use as a pioneer species (Kato <i>et al.</i>, 2007).</p>	<p>Berries have high vitamin A, C and E content (e.g., Gutzeit <i>et al.</i>, 2008, Kato <i>et al.</i>, 2007)). Potential use in cancer therapy (Olas <i>et al.</i>, 2018). Oil has been used in treatment of radiation burns (Pilát <i>et al.</i>, 2015) and of interest in skin protection from UV (Geçotek <i>et al.</i>, 2018). A potential crop for cold arid regions (Husain <i>et al.</i>, 2018), e.g., Martian ETNRs.</p>
<i>Adenocarpus foliosus</i>	<p>Relatively high-altitude N-fixing component of Macaronesian heaths.</p>	<p>Diversifies N-fixing component.</p>
Rosaceae	<p>Aesthetic value and many deciduous tree and shrub species of commercial importance for fruits. Cold-hardy cultivars exist for apples, sour cherries and plums, some considered hardy down to USDA Hardiness Zone 3 (-40 to -34.4°C) (e.g., Sutton and Dunn, 2021).</p>	<p>Seasonal fruits of anthropocentric value and increasing potential for possible animal colonists.</p>

(Continued)

Table 2. (Continued.)

Forest element	Taxon	Justification	Ecosystem services
	Shrub layer of <i>Juniperus tibetica</i> forest	<i>J. tibetica</i> forest is drought and cold tolerant with sparse shrub layer of <i>Berberis aggregata</i> , <i>Cotoneaster</i> spp., <i>Lonicera</i> spp., <i>Potentilla fruticosa</i> , <i>Ribes</i> spp., <i>Rosa omeiensis</i> , <i>Spiraea mongolica</i> and <i>S. alpina</i> . <i>Caragana</i> (see in table above), N-fixer , occurs at the driest and coldest extreme (Chen, 2015).	<i>Berberis</i> , <i>Cotoneaster</i> , <i>Lonicera</i> and <i>Rosa</i> as fleshy fruit-bearing species contribute to seasonal food sources for animals. Need for vitamin C (e.g., <i>Ribes</i> spp.) necessitates their presence.
	Ericaceae	Ericoid mycorrhizas enable Ericaceae to colonize acidic soils containing high levels of heavy metals (Bradley <i>et al.</i> , 1982). <i>Calluna vulgaris</i> (e.g., Leake <i>et al.</i> , 1989) and <i>Vaccinium</i> spp. (Freedman and Hutchinson, 1980) might thus contribute to an ericaceous shrub layer beneath open canopy or successional stage. Mycorrhizal associate <i>Hymenoscyphus ericae</i> confers some heavy metal resistance to its host (Mitchell and Gibson, 2006).	Food, flavour (e.g., <i>Vaccinium</i> spp., Sater <i>et al.</i> , 2020), seasonal colour, heavy metal tolerance (cf. canopy layer). Nectar (Power <i>et al.</i> , 2018).
Herb layer Diversifies niches and products. Enhances human experience.	C3 and C4 plants	Anatomical and biochemical adaptations divide plants into C3 and C4 types. C4 plants store CO ₂ as malate and photosynthesize with closed stomata, thus minimising photorespiratory losses, and making them better adapted to arid environments than C3 plants (e.g., Young, 2020). C4 trees are however rare, and woody C3 vegetation can outcompete lower growing C4 communities (Sage and Sultmanis, 2016). Most plants, especially of temperate landscapes, are C3. The efficiency of C3 photosynthesis increases as pO₂ falls from 210 to c. 20 mbar (Björkman, 1966). This offers potential advantages for a high-altitude type of environment with pO ₂ much less than the Earth's sea-level value of 213 mbar (e.g., Sharma and Hashmi, 2021). In C3 plants, elevated CO₂ increases photosynthesis (see Ainsworth and Rogers, 2007). The need to create a contained atmosphere from the native Martian high CO ₂ resource may lead to a higher than Earth CO ₂ component, so this facet of C3 plants may be beneficial for the forest. By contrast, C4 plants are in general relatively unresponsive to elevation of atmospheric CO ₂ above current ambient levels (Taub, 2010).	Diverse responses to atmospheric stressors offers insurance against unplanned variation in contained atmosphere.

Herb layer components of <i>Juniperus tibetica</i> forest	A selection of C3 and C4 plants is therefore proposed for a contained ETNR, providing a spectrum of tolerance to variance in water supply, available N and atmospheric O ₂ /CO ₂ variance. Herb layer of <i>Juniperus tibetica</i> forest includes <i>Andropogon munroi</i> (Poaceae), <i>Deyeuxia scabrescens</i> (Poaceae), <i>Kobresia</i> spp., (Cyperaceae) and species of <i>Anaphalis</i> , <i>Artemisia</i> , <i>Leontopodium</i> (Asteraceae), <i>Polygonum</i> (Polygonaceae), <i>Stellera</i> (Thymelleaceae) and <i>Thalictrum</i> (Ranunculaceae) (Chen, 2015). These offer a potential ready-mix of herb species for a facsimile high-altitude forest , meriting consideration due to co-evolution perspectives.	Poaceae and Cyperaceae offer ground cover , Asteraceae offer niche opportunities for insects. In UK, <i>Anaphalis margaritacea</i> is an invasive colonist of abandoned coal waste heaps, with nutrient-poor mineral soils and low water-holding capacity.
<i>Myrrhis odorata</i>	Native in woodlands (Watson, 2002) and hardy to USDA Hardiness Zone 5 (– 28.9 to – 23.3°C) (Missouri Botanical Garden, 2022c), <i>M. odorata</i> would provide ecological structure, aesthetics (white flowers) and utility (anethole, Ravindran <i>et al.</i> , 2012)) Astronauts’ cravings for spicy foods after periods in microgravity and comments on the ‘sterile’ smell of spacecraft (e.g., Romanoff, 2009) could become significant issues on long space missions. Strongly, but pleasant, smelling plants may be psychologically beneficial.	Herb substitute for anise or fennel, containing trans-anethole (Ravindran <i>et al.</i> , 2012) Widely used in foods and beverages, 13 times sweeter than sugar and with medicinal properties (Marinov and Valcheva-Kuzmanova, 2015), botanically derived anethole provides an option for ‘ Martian sugar ’.
<i>Digitalis purpurea</i>	Species of acidic soils (Smith, 2013), suitable for woodland, providing colourful flowers and nectar (e.g., Gaffal <i>et al.</i> , 1998). Hardy to USDA Hardiness Zone 4 (– 34.4 to – 28.9°C (Missouri Botanical Garden, 2022b).	Less demanding for high-altitude facsimile ecosystem than <i>Saccharum</i> spp. Source of cardiotonic glycosides (digoxin and digitoxin) used in treatment of heart disease (e.g., Patil <i>et al.</i> , 2013). Aesthetics and insect support.

(Continued)

Table 2. (Continued.)

Forest element	Taxon	Justification	Ecosystem services
	<i>Azorella compacta</i>	Surviving extreme high elevation (Atacama Desert), water scarcity, nutrient limitation, high UV flux, and reaching 3000 years old, compact cushion form allows decoupling of microclimate inside from surroundings (Pugnaire <i>et al.</i> , 2020). Might be used on forest periphery.	Survivorship.
	<i>Arenaria bryophylla</i> , <i>Sussurea gnapholodes</i> , <i>Lepidostemon everestianus</i> , <i>Androsace khumbuensis</i> , <i>Saxifraga lychnitis</i> var. <i>everestianus</i>	Highest vascular plants on Earth ; collected at c. 6400 m a.s.l. on Everest expeditions (Dentant, 2018).	Forest periphery species: insurance against pressure loss.
	Fabaceae from Canarian, oligospecific pine forests	N-fixing legumes of immature soils experiencing climatic and edaphic drought : <i>Lotus campylocladus</i> , <i>L. spartoides</i> from forests of endemic <i>Pinus canariensis</i> of dry montane level 500–2500 m a.s.l. (EEA, 2019). <i>L. campylocladus</i> is nectar source for insects (Dupont <i>et al.</i> , 2004a).	N-fixation, nectar, aesthetics.
	Herbaceous species from Canarian montane scrub	Tropical alpine vegetation experiences some of the highest UV-B irradiances on Earth's surface and constituent plants show high levels of UV protection (Barnes <i>et al.</i> , 2017), a useful character for Mars terraforming. Even assuming harmful UV is excluded, these have other useful adaptations. <i>Las Cañadas</i> (≥ 2000 m a.s.l.) (Tenerife) has well-drained, skeletal soils , strong UV, low precipitation and relative humidity (Dickson <i>et al.</i> , 1987). Subject to great diurnal and seasonal fluctuations in temperature (Fernandopullé, 1976; Ortuño, 1980), it supports species of value for an ETNR. Deep-rooted, thick cuticle, N-fixing, legumes (e.g., <i>Spartocytisus supranubius</i>), and species with dense, reflective epidermal indumentum (e.g., <i>Echium wildpretii</i>) have potential for stages of uncontained Martian terraforming. <i>E. wildpretii</i> produces nectar and is visited by birds and insects including honeybees (<i>Apis mellifera</i>) (Dupont <i>et al.</i> , 2004b). <i>Spartocytisus supranubius</i> is exploited in honey production (Bonvehí <i>et al.</i> , 2004).	UV resistance, skeletal soil tolerance, some N-fixers, nectar.

Ferns

Contained atmosphere is vulnerable to sub-catastrophic events including drastic humidity change, so biotic insurance requires inclusion of diverse species with different tolerances.

As seedless vascular plants, ferns inhabit temperate, desert and tropical environments, showing alternating, independent sporophyte and gametophyte phases. The latter, despite relative anatomical simplicity, can show **extreme desiccation tolerance**, growing where sporophytes cannot and sometimes perennating and waiting out stressful periods (Pittermann *et al.*, 2013). **Fern gametophytes have even retained viability after storage in liquid nitrogen** (Pence, 2000).

Photosynthetic gametophyte of *Trichomanes speciosum* can reproduce vegetatively, showing **extreme low-light adaptation**, surviving in norms of <0.01% full sunlight (Johnson *et al.*, 2000). Potential sub-catastrophic light loss due to dust storms or system failure merits its inclusion.

Some ferns tolerate **high altitude**, e.g., *Huperzia saururus* at 5200 m (Jacobsen and Jacobsen, 1989) and other high páramo species (Sánchez-Baracaldo and Thomas, 2014).

Bryophytes

Some mosses tolerate extreme environments (Glime, 2017).

Aulacomnium turgidum, *Distichium capillaceum*, *Encalypta procera* and *Syntrichia ruralis* **survived 400 years in glacial ice** (La Farge *et al.*, 2013), *Grimmia laevigata* 10 years herbarium storage (Keever, 1957). One *Grimmia* species survived exposure to liquid helium (Becquerel, 1951).

Huwe *et al.* (2019) report **limited exposure of *Grimmia* species to Mars-like atmospheres** did not affect photosynthetic activity, noting many *Grimmia* species occur in cold altitudes (to 5000 m a.s.l.), on basalt or granite, hair points providing **protection against UV and desiccating wind**. Such characteristics make good candidates for an ETNR.

Through reductive simplicity, Japanese moss gardens planted with *Polytrichum commune* (e.g., Schenk, 1997) offer ground cover and **psychological restoration**.

Poikilohydry, tolerance of freezing or desiccation and ability to reproduce asexually (Huwe *et al.*, 2019) offer additional biotic insurance, successful spore formation less critical to propagation. Inclusion of species with **N-fixing cyanobacterial**

Spore production diversifies propagule range. Alternating life stage requirements increases **potential to survive sub-catastrophic environmental fluctuations**. *T. speciosum* offers **darkness tolerance (photosynthesis in periods of light occlusion/delivery failure)**. Fern ground flora enhances visitors' forest experience.

Psychological restoration, aesthetics, ground cover, contribution to N-cycle.

Table 2. (Continued.)

Forest element	Taxon	Justification	Ecosystem services
Epiphytes and ground layer	Lichens	<p>associates (e.g., Adams and Duggan, 2008) offers pragmatic contribution to N-cycle.</p> <p>Many lichens can live and photosynthesize under low temperatures, aridity and high UV fluxes (de Vera, 2012). Mars Simulation Chamber experiments with extremophile, Antarctic <i>Pleopsidium chlorophanum</i> indicate Terran life could adapt to live on Mars (de Vera <i>et al.</i>, 2014).</p> <p>Cyanolichens incorporating cyanobacteria engage in N-fixation (Marks <i>et al.</i>, 2015). On Earth, cryptogamic covers (photoautotrophic communities including cyanobacteria, algae, lichens and bryophytes on surfaces) account for about half terrestrial biological N-fixation (Elbert <i>et al.</i>, 2012). Lichens will therefore be a valuable functional aspect of the ETNR, providing N-fixation, photosynthesis, niche diversity, colour and texture in a contained environment.</p>	Nitrogen fixation, niche diversification, colour and texture.
Microbiome	Mycorrhizal fungi	<p>Fungi's role in decomposition is discussed in the main text but mutualisms with plants are also critical. ETNRs require fungal associates of the constituent plant species, including heterogeneous mycorrhizal fungi. Associated with roots of >90% of plant species (Bonfante and Genre, 2010), these are critical to soil nutrient capture (e.g., Smith and Read, 2008), and some contribute to decay processes (e.g., Talbot <i>et al.</i>, 2008). <i>Hymenoscyphus ericae</i> is discussed under 'Ericaceae'.</p>	Root function, plant nutrition and decomposition.
	Bacteria	<p>Designing ETNRs' prokaryotic complement demands empirical development, experimentation, assembling unique complements of bacteria, fulfilling essential ecosystem functions, expecting unknown interactions, and essential redundancy. When planting a tree on Earth, supporting microbial diversity is expected, consciously or unconsciously, to be present. In ETNRs this cannot be assumed. Calculated lack of sterility is needed; the ETNR design must be 'down and dirty'. de Vera <i>et al.</i> (2019) suggest diverse microorganisms may survive (uncontained)</p>	Nutrient cycles, symbioses and synergies (some unknown), decomposition.

Invertebrates

Earthworms, generalist
pollinators and
comminutors.

Ethical parameters require species to thrive. As discussed, some insects learn to fly in microgravity (Nelson and Peterson, 1982; Vandenberg *et al.*, 1985). Effect of Mars' gravity on invertebrates is speculative but possibly less challenging than microgravity. Experiments will be needed to determine essential species complement considering seasonality, food sources, life cycles and containment limitations, as directed by the following:

Mars-like conditions for minimum 1.5 years, so choice exists. Lladó *et al.* (2017) review roles of soil bacteria in forests including **decomposition, N-fixation, C-sequestration, phosphorus cycling and mycorrhizal function**, different forest types and niches supporting specific communities. Plants are inhabited by critical microbiomes (including bacteria, archaea, fungi and protists) important to development, function, N-fixation, protection against pathogens, growth promotion and stress alleviation (Hardoim *et al.*, 2015). The importance of canopy microbes for plant health is not thoroughly investigated (Nakamura *et al.*, 2017).

Forest bacteria and other microorganisms able to interact and fulfil these different roles will be needed when, in some cases, the mechanisms by which this operates is not yet understood. Mars has resources needed by cyanobacteria with photosynthetic, N-fixing and lithotrophic abilities; these could produce food, fuel and O₂ for humans, organic matter from their growth supporting other organisms and **aiding soil formation** (Verseux *et al.*, 2016). Assimilation of **perchlorate-reducing proteobacteria** (e.g., Nozawa-Inoue *et al.*, 2005) into the ETNR provides additional insurance against toxic ingress.

Specific microbial integrants will be essential, but regolith inoculation with diverse Terran soils invites serendipity, unknown complexity demanding calculated randomness. Incorporation of **N-fixing bacterial symbionts** (*Rhizobium* and *Frankia* species for leguminous (Maróti and Kondorosi, 2014) and actinorhizal plants (Dawson *et al.*, 2005)) will be critical.

**Soil function, plant pollination,
population control, nutrient
cycling, decomposition,
psychological restoration,
biotic insurance.**

(Continued)

Table 2. (Continued.)

Forest element	Taxon	Justification	Ecosystem services
		<ul style="list-style-type: none"> Plants and soil biomes are linked by herbivores, pathogens, symbionts, decomposition and nutrient cycling (Sylvain and Wall, 2011). Invertebrates mediate decomposition, nutrient cycling and pollination. Value includes allospecific solace, inspiration and biotic insurance. However, soil invertebrates are diverse, sizes ranging across orders of magnitude (Lavelle <i>et al.</i>, 2006) and soil communities broadly (Decaëns <i>et al.</i>, 2006) encompass most terrestrial animal species. Evidence for which soil invertebrate activities affect plants is incomplete (Griffiths <i>et al.</i>, 2021) but even if all species' importance was known, selection would be challenging; deciding synergies and redundancies critical to TTE establishment. Minimal complements of volant, non-specialist pollinators, earthworms for soil aeration and comminution, ants and molluscs to contribute and predators to control populations are essential but assembly of a functioning forest invertebrate fauna demands experimentation. Estimates of soil biodiversity indicate thousands of invertebrates per site, plus unknown levels of microbes and protozoa (Menta, 2012). Lavelle <i>et al.</i> (1997) discuss invertebrates' importance as ecosystem engineers with roles in soil modification and microbial processes, and contributing to crumb structure, porosity and comminution. Nematodes, collembola, mites, earthworms and termites are important for decomposition (Landsberg and Gower, 1997) but links between soil animal diversity and vegetation are numerous, intricate and ancient (Sylvain and Wall, 2011). Inclusion of insect pollinators requires supply of year-round sources of suitable nectar and/or insect dormancy interludes. This requires sequential anthesis of appropriate nectar-bearing species during seasons of pollinator activity. Nectar composition varies between plant species, relating to pollinator species exploited 	

(e.g., Dupont *et al.*, 2004a), and its chemistry influences pollinator behaviour in complex ways (Nepi *et al.*, 2018). Nectar sources and chosen pollinators must be compatible.

- Generalist invertebrate predators (e.g., spiders) offer population control. Orthoptera, would contribute restorative **aural distraction**. **Desiccation and radiation tolerant** tardigrades (Jönsson *et al.*, 2008) offer biotic insurance.

Non-human vertebrates omitted as ability to engage in natural behaviours is not ensured.

2014). Similarity of day length of Mars and Earth (Table 1) suggests adaptation may occur in CTTEs, processes according with the same temporal cues (*zeitgebers*).

However, the lunar cycle is also relevant. Earth's moon, Luna, is a *zeitgeber* for many ecological processes, some pertaining to monthly or half monthly cycles, others to shorter periods (e.g., Raible *et al.*, 2017). Examples include animals (e.g., Raible *et al.*, 2017; Sinclair, 1977; Dixon *et al.*, 2006) and plants (e.g., Barlow, 2015; Ben-Attia *et al.*, 2016). Lunisolar tidal force may also influence plant growth (Barlow and Fisahn, 2012).

Mars' two moons, Phobos and Deimos, have maximum radii of c. 13.5 km (NASA, 2019c) and c. 7.5 km (NASA, 2019d) respectively, small compared to Luna's radius of c. 1737 km (cf. Williams, 2021c). Rao (2015) speculates there are parts of Mars from which the moons are never visible due to orbital proximity and Mars' curvature.

Evidence for organisms' responses to Earth's lunar cycle varies from well substantiated to speculation but inevitably Terran species, translocated to Mars, would experience a different lunar influence, the effects hard to predict.

Soil

TTEs require suitable organic substrate. Freight constraints require local development. Mars has a basaltic upper crust, with variable abundances of other materials (Ehlmann and Edwards, 2014). Basalt-derived soils with volcanic ash are good agricultural soils (e.g., Olowolafe, 2002). Crushed basalt can increase soil pH, while its dissolution releases beneficial nutrients, including phosphorus (P) (Shamshuddin and Che Fauziah, 2010).

Martian substrate probably contains nutrients to sustain plant growth (e.g., Jordan, 2015). 'Mars regolith simulant', supports angiosperms (Wamelink *et al.*, 2014) and, with added organic matter, earthworms (Wamelink *et al.*, 2022).

Plants require 16 essential elements, C, hydrogen, O₂, nitrogen (N), P, potassium, calcium, magnesium, sulphur, iron, zinc, manganese, copper, boron, molybdenum and chlorine (Uchida, 2000). These are all reported from Mars or Mars meteorites (Jordan, 2015). Cobalt and nickel (e.g., Brown *et al.*, 1987; López and Magnitskiy, 2011) are also relevant, being involved in biological N-fixation. Nickel has been detected in Martian substrate (Gellert *et al.*, 2006; Yen *et al.*, 2006) and cobalt in putative Martian meteorites (Lodders, 1998).

Plant growth requires reactive N, predominantly nitrate (NO₃⁻); 40–60 ppm NO₃⁻ advised for vegetable crops (Cantisano, 2000). Evidence suggests up to c. 1100 ppm of NO₃⁻ in Mars' sedimentary deposits (Stern *et al.*, 2015).

Phosphates are essential for Earth life (Tirsch and Airo, 2014). Evidence indicates Mars is 5–10 times more phosphate rich than Earth, mineralogical studies (Adcock *et al.*, 2013) suggesting biological accessibility.

So Martian regolith may contain necessary nutrients for a CTTE, while low organic C, water holding capacity and cation accessibility might be improved by microbiological weathering (Cockell, 2011).

Cyanobacteria are proposed for *in situ* resource processing (Verseux *et al.*, 2016). Photosynthetic, N-fixing *Nostoc*, will grow on Martian regolith simulant (Arai *et al.*, 2008) and early successional cyanobacterial communities improve soil moisture retention (Danin *et al.* (1998).

Toxicity

Martian substrate contains perchlorates (ClO₄⁻) at concentrations much higher than typically found on Earth (Davila *et al.*, 2013). These affect thyroid function (e.g., Srinivasan and Viraraghavan, 2009) and some plant growth experiments with regolith simulant assume remediation (Gibbens, 2017). Other oxidants present at Mars' surface include hydrogen peroxide and iron oxides (e.g., Lasne *et al.*, 2016). Mars has over twice as much iron in its outer layers as Earth (Peplow, 2004) and, though an essential plant nutrient, it can accumulate to become toxic (Connolly and Guerinet, 2002). In combination, iron

oxides, hydrogen peroxide, perchlorates and Mars' UV flux, are highly deleterious to living cells (Wadsworth and Cockell, 2017). Extreme salinity is another potential stressor (e.g., Ramírez *et al.*, 2017).

Tolerance of such parameters will be desirable in ETNRs, though CTTEs allow remediation. Many perchlorate-reducing bacteria exist (e.g., Coates and Achenbach, 2004) and bacterial enzymes have potential to detoxify hydrogen peroxide (Nóbrega and Pauleta, 2019). Perchlorate is also highly soluble in water (Davila *et al.*, 2013), allowing biotic and/or abiotic decontamination.

Water

Present Mars is a cold desert (McKay, 2010). However, the freshwater content of Mars' permanent north polar ice cap is c. 100 times that of the Laurentian Great Lakes (Rummel *et al.*, 2014). Liquid water may even exist beneath the southern polar ice (Orosei *et al.*, 2018) and 'recurring slope lineae' may be active surface brine flows (e.g., Ojha *et al.*, 2015).

Evidence indicates sufficient water reserves for CTTEs (toxin removal possible). Conifer needles collect cloud drops (Unsworth and Wilshaw, 1989) suggesting delivery options. Atmospheric temperature gradients with dew points (Lu and Ho, 2019) and microstalactite ceiling materials (condensation foci) merit exploration for artificial rain.

Di-oxygen (O₂) and di-nitrogen (N₂)

Mars' atmosphere is CO₂ rich with little O₂ or N₂ compared to Earth (cf. Table 1). O₂ is essential for aerobic TTEs, while relatively inert N₂ is useful in bulking atmospheric pressure. Reactive N is present in proteins and nucleic acids, so sufficient atmospheric N₂ must be available for biological N-fixation (McKay and Marinova, 2001) and cycling. CTTEs on Mars therefore require increased atmospheric O₂ and N₂.

Fortunately, Mars' resources include oxygen bound in perchlorate, carbonate (Bridges *et al.*, 2019) and nitrate (the latter providing fixed N) that might be harvested. Davila *et al.* (2013) propose enzymic release of O₂ from perchlorate and N₂ might be liberated by bacterial denitrification (e.g., Hart *et al.*, 2000). Technologies are also developing for mining Martian atmosphere (Finn *et al.*, 1996; Sridhar *et al.*, 2000) and CTTEs do not necessitate duplication of Earth's mean atmospheric pressure and composition; atmospheric pressure varies altitudinally and species' tolerances vary.

Klingler *et al.* (1989) showed some bacteria capable of N-fixation from partial pressures of N₂ down to 5 mbar (25 times current Mars levels). Some plants can utilize O₂ levels well below, and tolerate CO₂ levels above, current Earth values. Photosynthesis can be enhanced at O₂ concentrations below ambient (e.g., Downes and Hesketh, 1967), due to reduction in photorespiration (e.g., Hagemann *et al.*, 2016). Some show higher photosynthetic rates under elevated CO₂ (e.g., Ainsworth and Rogers, 2007), benefiting from the 'CO₂ fertilization effect' (Zheng *et al.*, 2018).

Green plant photosynthesis might generate elevated O₂ levels in a CTTE. Fogg (1995) considered root respiration demand could limit plant growth on Mars until atmospheric O₂ was raised to 20–100 mbar (>3000 times current levels) but levels in containment could be primed.

Modification of contained Martian atmosphere is therefore conceivable and may be less demanding than anticipated. As initial O₂ levels rise, and biological N-cycle initiates, photosynthetic eukaryotes may mediate further atmospheric modification, ultimately achieving conditions tolerable by invertebrates.

Gravity

Terran life evolved within Earth's gravitational field (1 g) and CTTE success depends on development and function under Mars' lower gravity (Table 1).

Light and gravity modulate plant development (Vandenbrink *et al.*, 2014). Experiments indicate 0.3 g (< Mars) sufficient to trigger gravitropic responses, but that meristematic competence can be lost under

lunar-like (0.17 g) gravity (Manzano *et al.*, 2018). Nevertheless, plants will grow and photosynthesize even in microgravity (e.g., Monje *et al.*, 2005; Wolverton and Kiss, 2009). Though some biochemical (Cowles *et al.*, 1988) and anatomical (Hoson *et al.*, 2003) changes may occur, results conflict (Stanković, 2001).

From such evidence, it is conceivable that some plants (and fungi, cf. Kern, 1999) will tolerate Mars' gravity. However, forest function is also influenced. Leaf and propagule fall, leaping, flight, deadwood collapse, raindrop impact and drainage of water contribute dynamism. On Mars, things weigh 38% their Earth weight, potentially benefitting trees etiolated by low light, or lacking wind-induced reaction wood (Groover, 2016) (cf. Biosphere 2, Nelson, 2018).

Many organisms reproduce and disperse by airborne propagules. If these develop normally, greater dispersal capacity under lower gravity may not be problematic, provided they *can* disperse. This may require vectoring to avoid intergenerational competition, so, CTTEs need wind. However, lower gravity means lighter propagules and thermal gradients might be exploited to generate air currents.

Some plants and fungi exploit 'splash cups' from which propagules are dispersed by raindrop impact (Brodie, 1951). Such structures evolved in response to rain falling under 1 g, their functionality on Mars unknown but testable.

Potential to leap, climb or fly on Mars with less effort will influence TTE function and some animals may benefit from positive energy budgets. Some insects learn to fly in microgravity (Nelson and Peterson, 1982; Vandenberg *et al.*, 1985), so potential exists. Capacity of most animals to adapt is unknown but 0.38 g is not zero g.

Forest design

Species complement dictates forest appearance, physiognomy and functioning. Limited by the abiotic environment sustained, this will perforce include an unusual assemblage of species (integrants), tolerant of prevailing conditions, comprising a novel ecosystem. On Earth, species niches are limited by competition and availability. Local environmental parameters in CTTEs will lead to new fitnesses, species occupying different roles where niche requirements are provided.

It would be counterproductive to plan replication of a specific forest biome. Earth's forests owe their assemblages to environmental and evolutionary pressures that will differ to those in Martian CTTEs. No single forest food web has been fully mapped, canopies themselves potentially comprising over 100 000 trophic links (Nakamura *et al.*, 2017), challenging duplication. Lack of GMF, reduced sunlight, aberrant seasons, variant lunar cycle, reduced gravity and pedological peculiarities will engender novel ecosystem function.

Significant seasonal differences make it unlikely the same palettes of synchronized mutualisms, which define Earth's forests, could be established on Mars, though dormancy traits might prove useful (e.g., Taylor, 1998) and potentially some species would adapt. If so, a forest might be established but it would only consist of those organisms than *can* adapt. Design must therefore include planned redundancy, allowing for unknowns.

Mitsch and Jørgensen (2003) indicate that if enough organisms and propagules are delivered, local conditions will select out the best-adapted assemblage. In Odum's (1983) terminology, ecosystems self-organize from the available (Smith, 2018 discusses) and designers must allow 'self-organization' since active assembly of complex species networks would demand unattained prescience.

ETNR designers should consider species as ecological cogs that might be assembled into functional ecosystems. Replication of Earth forests is currently unfeasible but development of new ecosystems, functioning in unexpected ways, is conceivable. Mars' forests would not resemble or function exactly like Earth's forests but could still deliver wonder; autumn at 0.38 g offering dreamlike leaf fall.

Early ETNRs may be relatively oligospecific, freighting considerations, even for seeds, restricting initial complement. Selection must acknowledge survivability and ecosystem function, while expedience requires instrumental value, species producing wood, fibre and important secondary metabolites

(vitamins, flavours, perfumes, colours, mood enhancers). Species diversity must be built incrementally, over time, by assisted colonization, monitoring, adjustment and replenishment.

The proposed forest is intended as an expansion of Earth's ecosystem, a utilitarian botanic garden and restorative sanctuary. Arboreal communities that can be 'entered', offering a sense of 'escape' support the latter, several tree taxa proposed as canopy. The design incorporates some organisms considered problematic on Earth but exhibiting potential ET adaptability or terraforming value. Heretical recombination is incited, selecting species from various forest biomes to exploit useful traits, fulfilling essential roles. On Earth, ecosystems rely on co-existence for services including N-fixation and mineral breakdown but in a CTTE all needs must be met either artificially or by integrants. Experimentation will be necessary, knowledge accruing, anticipating subsequent ecosystem modification.

Varietal forests adapted to extreme ambient parameters offer templates of resilience. High-altitude forests tolerate low atmospheric pressures and temperatures. Early successional forests exploit soils low in nutrients and sometimes high in heavy metals. Attempted duplication of a specific high-altitude ecosystem has merit in that species complement can be determined, co-evolution satisfied and incompatibilities minimized. However, this does not allow selective assembly, failing to acknowledge precedent diasporic Earth forest (Smith, 2018) and unique Martian exigencies.

Species complement

Mars' forest complement is designed with reference to local constraints, instrumental value and survivability (Fig. 2). The assemblage is broadly justified below and detailed in Table 2.

Trees of high altitudes provide the foundation. Earth has elevational limits beyond which trees cannot grow (Körner, 2012). About 100 species worldwide form trees at the climatic treeline, reducing to c. 20 (Pinaceae and Betulaceae) at the arctic equivalent, (Körner, 2012). Miehe *et al.* (2003, 2007) discuss high-altitude Tibetan forests, including the sacred Reting Forest, where *Juniperus tibetica* (Cupressaceae) grows in an open shrub layer of *J. pingii* var. *wilsonii*, *Potentilla fruticosa*, *Lonicera* spp. and *Caragana* spp. Two junipers, *Juniperus convallium* (3500–4570 m a.s.l.) and *J. tibetica* (4100–4850 m a.s.l.), are widespread in southern Tibet (Miehe *et al.*, 2003). They form small forests, sometimes amongst *Picea* and in open stands of *Cupressus torulosa* var. *gigantea* (Farjon, 2010). *J. tibetica* forms the highest northern hemisphere treeline (e.g., Miehe *et al.*, 2007), some stands being pilgrimage sites (Miehe *et al.*, 2003) or religious landmarks (Miehe *et al.*, 2008).

Climatic limits of cold timberlines relate to isotherms of 10°C for warmest month's mean temperature (Daubenmire, 1954). Similar mean growing-season temperatures of c. 6.7°C, at climatic, high-elevation treelines worldwide indicate temperature control (Hoch and Körner, 2005). Rainfall data suggest the drought limit of juniper trees correlates with annual precipitation of 200–250 mm and Miehe *et al.* (2003) argue the high mountain deserts of southern Tibet could be reforested without irrigation, even lacking a high groundwater table.

Mars' soils will shape the contained forest, so, early successional colonizers, common to high altitude environments, e.g., pines (*Pinus* spp.) and birches (*Betula* spp.) are included. Substrate pH constrains species choice. Contained soils may be modified but minimal intervention is expedient. Phoenix Mars Lander measured an alkaline pH of 7.7 ± 0.5 for substrate (Hecht *et al.*, 2009) whereas Opportunity rover found evidence of slightly acidic to circum-neutral pH (Arvidson *et al.*, 2014), so soils of varying pH could be developed allowing species diversity.

Juniperus tibetica grows on rocky soils derived from siliceous and calcareous materials, experiencing extremes of solar radiation and frost (Farjon, 2010) but CTTEs might also incorporate canopies from high altitude heaths, i.e., *Erica arborea* or *E. trimera* (e.g., Beentje, 2006). Ericaceous plants' tolerance of acidic, metalliferous soils (Bradley *et al.*, 1982) may be useful. N-fixing plants will also be essential. The N-fixing shrub *Caragana versicolor*, tolerant of Himalayan cold aridity (Kumar *et al.*, 2016), is proposed for clearings and margins.

Creation of ETNRs as biotic insurance against planetary disaster requires human redundancy, currently unachievable. A biocentric ideal would be a self-monitoring, self-repairing containment

able to support a living ecosystem even following human abandonment. However, this would represent a pyrrhic legacy if the containment survived an event, its ecosystem extirpated. CTTEs should include some species resilient to sub-catastrophic containment failure, providing opportunity for re-establishment in the manner of Terran ecosystems post adversity.

Plants categorized in USDA Hardiness Zones 1a to 7b (USDA, 2012) offer potential for survival of unplanned temperature drops, these covering species able to survive average, annual winter temperatures of -51.1 to -12.2°C . Choice of range is subjective but -12.2°C must offer 'some' insurance against partial containment failure (increasing levels below that). This provides significant opportunity for the development of boreal forest types, dominated by conifers but with associated broad-leaved plants.

Long-lived seeds, able to withstand deep cold, O_2 starvation, fire and/or decompression and to subsequently germinate, would contribute to recovery from temporary containment failure. Ability to resprout from hypogean structures (e.g., James, 1984) would also be useful. A mixture of species, resilient to periods of reduced atmospheric pressure, darkness, desiccation or other extremes, facilitates biotic insurance, i.e., however severe life support failure is, something will survive.

Individual longevity is desirable in certain integrants. Initiating ancient tree development would provide visionary opportunity. Intangible though such issues are, ancient trees may ultimately engender historical connection between CTTE designers, facilitators and future visitors, potential for legacy, a harnesser of political and financial support.

Junipers are long-lived. *J. communis* can live c. 200 years (Ward, 1982), *J. pingii* var. *wilsonii* >300 years (Liang *et al.*, 2012). Dendrochronological analysis provides ages >2000 years for *J. occidentalis* (Rocky Mountain Tree-Ring Research, undated) and >2230 and 1265 years for *J. przewalskii* and *J. tibetica* respectively (Liu *et al.*, 2019). By vegetative reproduction, some trees persist as clonal organisms for centuries. A *Populus tremuloides* clone in North America, extending over 43.6 hectares (DeWoody *et al.*, 2008), is potentially of great age (Rogers and McAvoy, 2018).

Fecundity is important in future proofing. Rapidly reproducing plant species can repopulate in the event of non-critical losses. Less fecund species may be vulnerable to vicissitudes of population decline, entering extinction debt in the event of partial catastrophe. Rapidly propagating species (e.g., *Betula* spp.) should therefore be included.

ET ecosystem design philosophy is nascent. Just as some plants develop winter hardiness, surviving freezing (e.g., Vitasse *et al.*, 2014), unexpected phenotypic adaptations to other stressors might be expressed in ETNRs. Such unpredictable phenomena make the difference between success and failure, so adaptability is important and 'invasiveness' on Earth may be a valuable trait in ET environments.

To facilitate ecosystem construction, some understorey species are selected with consideration to natural occurrence alongside canopy integrants. Necessity to avoid allelopathic incompatibility motivates this, though, notably, some invertebrates require multiple plant species for life cycle completion. Such niche requirements could be difficult to fulfil but experiment may reveal unknown tolerances and suitabilities, while selection of some naturally co-occurring plant species may assist.

Use of extremophiles from Mars-like, high-altitude deserts on Earth is not emphasized. Though replication of cold desert ecosystems might be easier to achieve on Mars than forests and would offer biotic insurance, it is arguable whether similar psychological and inspirational benefits would ensue. Recreation of non-forest ecosystems on lifeless planets is laudable, a responsibility inherent to humanity's burgeoning space-faring ability, but the creation of wonder and incitement to pilgrimage require a physically imposing plant community; this demands trees.

Acknowledging the issues above, Table 2 presents a forest-like assemblage incorporating biodiversity, resilience and functionality. Human psychological restoration requires interest and distraction, variation in colour, hue and form, species variety and opportunity for haptic exploration, so these are integrated. Ecosystem services that integrants could supply, relating to human life support and life quality are listed.

ET forest (ETF) survival requires future proofing against system failures. Political support dwindles less if such failure is only partial. Trial and error will shape the species palette, but that presented plans

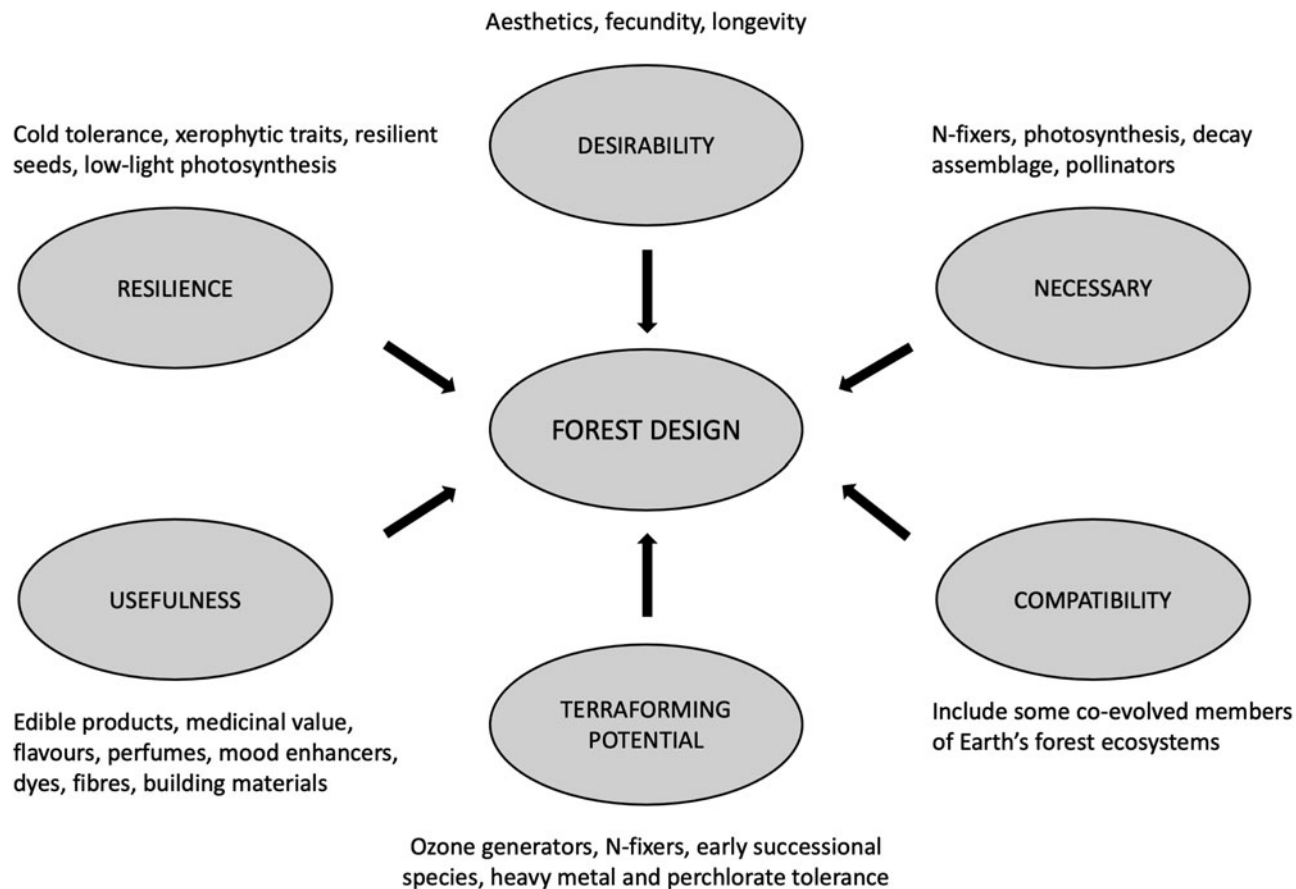


Fig. 2. Selection factors for Mars' forest species complement based on local constraints, instrumental value and survivability.

for unmitigated success and limited catastrophe. Since all photosynthetic plants provide O₂ and absorb CO₂, this major ecosystem service is common throughout. Designers must note that dioecy sometimes demands two genders.

Decomposition

Decomposition must occur in CTTEs. Without breakdown of dead biological material, nutrients become sequestered, atmospheric CO₂ depleted and ecosystem cycling ceases (e.g., Chapin *et al.*, 2002). Table 2, therefore includes decomposers.

Organic litter fall is crucial in biogeochemical cycling (e.g., Krishna and Mohan, 2017). Arthropod communities mediate its degradation (e.g., Berg *et al.*, 1998). Litter and deadwood are also C sources for forest soil microbes (e.g., Lladó *et al.*, 2017). Kjølner and Struwe (1992) discuss microfungi's key role in degrading diverse complex molecules. Bacteria are also important, especially in the soil N-cycle (e.g., Takai, 2019).

CTTE designers must provide suitable biota able to carry out decomposition processes (disassembly, fragmentation, trituration, digestion, solution and N-cycle steps from ammonification to denitrification). The risk of N-cycle dysfunction requires monitoring and proactive correction technology may be necessary, diverging from ideals of human redundancy. With Earth's functional biogeochemical cycles, creation of a forest ecosystem is readily conceivable but incorporation of such support into CTTEs poses challenges.

Ethics

Whether an ETNR is ecologically effective depends on scale. Optimal size of Earth nature reserves is debated (e.g., Diamond and May, 1981; Higgs, 1981) and ETNRs demand similar scrutiny. Size of CTTEs may be limited by engineering constraints, but 'minimum-area requirements' and 'minimum viable population' sizes will be relevant, as per the SLOSS debate (i.e., whether a single large reserve will conserve more species than several small, e.g., Tjørve, 2010).

To provide biotic insurance ETNRs require assemblages from all Kingdoms of living things including animals. This raises ethical issues, ecosystem dysfunction potentially leading to suffering through system failures, unsuitable design or intolerances.

In facilitating psychological recovery of space workers, animals would be beneficial. Woodland without birdsong or butterflies is a poor TTE. Such lack may exacerbate homesickness. However, when creating habitats on Earth, many animals can elect to inhabit or leave by their own volition. This choice is denied in a CTTE. Introduction of species unable to engage in natural behaviours should be avoided, consideration of the 'five freedoms' (Farm Animal Welfare Council, 1993; Webster, 2016) will be necessary and human management may be essential.

Consequences of contact between biospheres is also a consideration, as reflected in the UN's Outer Space Treaty of 1967 (United Nations, 1967) and the International Council for Science's Committee on Space Research (COSPAR) Planetary Protection Policy (COSPAR, 2002 (amended 2011), Rummel *et al.*, 2014). Creation of contained biospheres reduces risk of ecosystem contamination but, since no containment is perfect, protection of Mars' 'Special Regions' (Rummel *et al.*, 2014) influences location choice.

Conclusions

Creating a contained ETF is more complex than establishing woodland plants in a protected environment. Even gardens rely on natural nutrient cycling, soil disturbance and irrigation. CTTEs should be almost self-sustaining with propagule dispersal vectors, internal weather and replication of the myriad changes that forests exploit. The designers' task is daunting but, if survival of Earth life is to be ensured, challenges must be overcome.

Humanity does not know if life exists elsewhere in the universe. Mars may support native organisms, but even if it does, Earthly life may be endemic to Earth. Perhaps, life only exists on Earth. In either of which cases, *Homo sapiens* as the local sentient, technologically empowered species, has responsibility.

From a biocentric perspective, world leaders should be concerned about the future of life in the Universe and humanity's role in its protection and promulgation. On a planet of limited habitability, this is a significant duty. The survival of life, in any form, is the ultimate biocentric priority.

The global ecosystem changes and its conservation requires imagination. Evidence indicates that a contained ETF could be established on Mars. A partially human-redundant protection system would be needed but, like the juniper forests of Tibet, the forest's existence would incite pilgrimage, emboldening efforts for space travel. It is easier enter a desert, knowing it contains an oasis.

This paper does not consider economics. Sending humans into environments without ecosystem services adds to space travel's cost (e.g., Glenn Smith and Spudis, 2015). ESA's MELiSSA project indicates that humans should not think of travelling alone but with a supporting biosphere. We travel through space every moment, sustained by Earth's biodiversity. Our planet carries a self-supporting, bioregenerative ecosystem that, accepting Lovelock's (1979) Gaia hypothesis, modifies and sustains its own life supporting qualities. So, spacecraft should be reimagined as symbiotic communities.

The sailing ships of past explorers were not sterile. They carried animals for food and as living cargo (e.g., Blancou and Parsonson, 2007), for companionship (Mäenpää, 2016) and as pests (e.g., Atkinson, 1973). Sometimes, animals were released or escaped onto foreign shores where some thrived or became problematic (e.g., Campbell and Donlan, 2005; Harper and Bunbury, 2015), examples of accidental, incidental and deliberate dispersal of Terran species. Goats were once purposely liberated on remote islands by mariners, as a self-renewing food resource (Dunbar, 1984). Such attitudes may become necessary during space exploration, creating oases on barren but habitable planets. Spacecraft will carry multiple species complements, contributing life support for long journeys and on arrival at lifeless destinations.

ETNR design will be inspired by human dependency on ecosystem services, even in purely utilitarian fashion, because, despite technology, that dependence cannot be shed. We need plants as chemical factories, producing secondary metabolites with greater ease and more autonomy than industry. Ultimately, humans must take Earth's ecosystem with them, acting as the medium through which it colonizes the planetary archipelago of space. We will not travel alone because we did not evolve in isolation. *Homo sapiens* was shaped, over aeons, by other species and will travel with a mutually supportive system of Terran organisms amongst which we fit, exchanging metabolites as we have evolved to do. It is not humanity that is reaching out from Earth, it is life, with all its diverse capabilities for colonization, humanity the ineluctable vector.

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