

Can CO₂ be Used as a Pressurizing Gas for Mars Greenhouses ?

Raymond M. Wheeler
NASA Biomedical Office
Kennedy Space Center
FL 32899 USA
raymond.wheeler-1@ksc.nasa.gov

Background

The possibility of using plants to provide oxygen (O₂) and food during space travel has been discussed and studied for nearly 50 years (Myers, 1954). The concept is based on the process of photosynthesis, which uses CO₂ as a substrate and is driven by light (photosynthetically active radiation—PAR) in the 400 to 700 nm waveband (Galston, 1992). In addition to the CO₂ and light, the plants would require a controlled environment with acceptable temperatures (~10 to 35°C) and humidities (~40 to 85%) (Tibbitts and Kozlowski, 1979), adequate supplies of water and mineral nutrients (Marschner, 1995), and minimum levels of oxygen to sustain respiration (Siegel et al., 1962; Musgrave et al., 1988; Schwartzkopf and Mancinelli, 1991).

Because the atmospheric pressure of Mars is likely too low (0.6-1.5 kPa; McKay, 1984) to sustain acceptable plant growth (Andre and Richaud, 1985; Schwartzkopf and Mancinelli, 1991), and plant growth modules on Mars would need to be pressured to some level. This might be achieved by regular additions of some inert diluent gas, such as N₂ or Ar. Both nitrogen and argon are present in the Martian atmosphere, but in small quantities (2.7% and 1.6%, respectively; McKay, 1984). Hence it might be difficult to obtain adequate supplies of these gases. In contrast, CO₂ is relatively plentiful on Mars—0.95% of the atmosphere. Could this CO₂ be used as a pressuring gas? Clearly CO₂ is not biological inert, but a continuous supply of CO₂ would be needed to sustain plant photosynthesis and using it as a pressurizing gas could also satisfy this requirement. Assuming a Martian plant growth module is designed to operate at 20 kPa total pressure, perhaps at least 5 kPa of this would need to be O₂ to sustain plant (especially root-zone) respiration (Siegel et al., 1963; Musgrave et al., 1988), and up to 2 kPa would have to be water vapor to maintain adequate relative humidity in the module and avoid plant stress (Andre and Richaud, 1985). If CO₂ were used as a pressurizing gas, it could comprise up to 13 kPa of the 20 kPa atmosphere. At Earth ambient pressures, this would equate to 130,000 ppm of CO₂, or over 300 times the current concentration of about 360 ppm.

CO₂ Effects on Plants

The effects of CO₂ on plants have been widely studied and the research literature is extensive. Among the most commonly observed effects of increased CO₂ are increased photosynthesis (for C₃ plants) and decreased transpiration (Wittwer and Robb, 1964; Hicklenton, 1988; Drake et al., 1996). These changes typically occur as CO₂ is increased from ~300 ppm (0.03 kPa) to about 1000 ppm (0.1 kPa). As a consequence, many controlled environment plant production systems on Earth (e.g., commercial greenhouses) enrich CO₂ concentrations to increase photosynthetic rates and overall plant growth (Wittwer and Robb, 1964; Porter and Grodzinski, 1985; Hicklenton, 1988). But there is little advantage to going to levels much greater than 2-3 X ambient and few terrestrial greenhouses enrich CO₂ much above ~1000 ppm (0.1 kPa). Consequently, there are relatively few studies of plant responses to CO₂ concentrations >0.2 kPa (Wheeler, 1993; 1999).



Figure 1. Leaf bleaching on soybean noted at high CO₂ (0.5 kPa) partial pressures. Rusty flecks / spots are typical of normal senescence.

Our research group at NASA's Kennedy Space Center has been interested in the effects of super-elevated or supraoptimal CO₂ concentrations for a number of years, primarily because of the high CO₂ concentrations encountered in human-habitats in space environments. For example, CO₂ concentrations in NASA's Space Shuttle Orbiter commonly range from 0.4 to 0.6 kPa, and occasionally exceed 1.0 kPa (Wheeler et al., 1993). When we grew soybeans at a range of CO₂ concentrations, the upper canopy leaves showed some premature senescence and bleached, necrotic areas at the highest CO₂ level—0.5 kPa (Wheeler et al., 1993) (Fig. 1). This occurred during late pod fill of the plants and consequently had no significant effect on plant biomass or seed yield (Table 1). Subsequent studies with potatoes (Mackowiak and Wheeler, 1996) and radish (Mackowiak et al., 1996) showed similar injury at 1.0 kPa (10,000 ppm) CO₂. This result was not surprising based on other reports of possible CO₂ toxicity to plants (Berkel, 1984; Ehret and Jolliffe, 1985; Hicklenton, 1988; Bugbee et al., 1994). (Note, toxicity implies a substance is beyond the "sufficiency" level, or supraoptimal, but not necessarily at lethal levels). Most of our studies were conducted at a light level of $\sim 300 \mu\text{mol m}^{-2} \text{s}^{-1}$ PAR with a 12-h photoperiod, or about $13 \text{ mol m}^{-2} \text{day}^{-1}$ of total light. This is a relatively low total light level, which may have minimized potential injury at the high CO₂ levels, and additional studies are needed with super-elevated CO₂ at higher light intensities Wheeler et al., 1999).

Table 1. Biomass yields, water use, and water use requirements (water needed per unit biomass) of soybean and potato plants grown at different CO₂ partial pressures.

Crop	CO ₂	Total Dry Mass	Total Water Use	Water Use Requirement
	(kPa)	(kg)	(kg)	(kg g ⁻¹)
Soybean	0.05	2.04	845	414
	0.10	2.49	822	330
	0.20	2.27	879	387
	0.50	2.27	1194	526
Potato	0.05	3.25	483	149
	0.10	4.02	573	142
	0.50	3.66	916	250
	1.00	4.04	910	225

A more surprising observation from our studies was a significant increase in leaf transpiration and plant water use at the super-elevated CO₂ concentrations (e.g., 0.5 – 1.0 kPa) for most of the species tested (Table 1). This was a result of high stomatal conductance, i.e., the stomatal pores were more open (Wheeler et al., 1999) (Fig. 2). Although the stomatal conductance is also high at low CO₂ concentrations (e.g., 0.05 kPa), the stomata at these lower concentrations close during dark cycles (Wheeler et al., 1999). But this dark period closure does not occur or is incomplete with soybean, potato, radish, or sweetpotato at 0.5 and 1.0 kPa CO₂. At present, we still do not understand why this occurs.

Are High CO₂ Concentrations Tolerable in a Mars Plant Production System ?

The observations from these studies suggest the transpiration for many species will be high at very high CO₂ concentrations (e.g., > 1.0 kPa). This may not be a concern in terrestrial, hydroponic systems where ample water is available, but presents a challenge for space-based systems where water supplies are limited and rapid recycling is essential. Moreover, a consistent observation from low pressure studies with plants is that transpiration tends to rise due to increased gas diffusion rates between leaves and the surrounding atmosphere (Gale, 1973; Daunicht and Brinkjans, 1992; Corey et al., 1996). Thus if plants are grown at low pressures (e.g. 20 kPa) in an atmosphere where CO₂ is higher than ~0.5 kPa, plant watering requirements could be high. This could be offset somewhat by raising humidities in the plant modules, but maintaining high humidities may be difficult at lower pressures where heat exchange systems tend to condense humidity from the air very rapidly (see Fowler, this proceedings).

Do these findings preclude the use of CO₂ as a pressuring gas for Martian greenhouses? Carbon dioxide is readily available from the Martian atmosphere and could be provided by compressors/collectors envisioned for *in situ* propellant production systems. Use of local CO₂ could reduce or eliminate resupply gas costs and improve the economic feasibility of plant production systems. In addition, if a high proportion of O₂ is required for low-pressure atmospheres, high concentrations of CO₂ could provide some fire protection (quenching) advantages over Ar or N₂, but this would need to be determined. The leakage rates of different gases through component materials would also need to be compared. But, plant tolerance to very high CO₂ levels remains key. The fact that wheat showed no apparent injury and only moderate changes in transpiration at very high CO₂ suggest that capabilities exist for plant tolerance to super-elevated CO₂ (Bugbee et al., 1994; Grotenhuis and Bugbee, 1997).

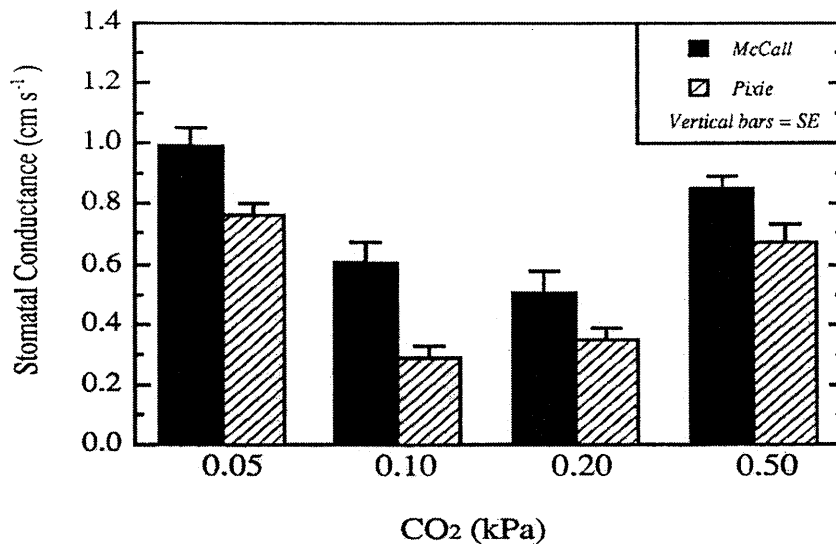


Figure 2. Stomatal conductance of two cultivars of soybean (McCall and Pixie) at different CO₂ partial pressures.

Alternatively, *in situ* gas compressing / collecting systems might produce sufficient Ar or N₂ to pressurize plant production modules. This could avoid the need for maintaining very high CO₂ pressures, but complicate the systems somewhat by now requiring CO₂ control (for photosynthetic needs) and separate pressurizing-gas controls. In addition, use of Ar would require testing to assess the effects of Ar-enriched atmospheres on plants. For example, as with CO₂, Ar is heavier than N₂ and would alter boundary layers around leaves, which in turn would affect gas diffusion and convective heat exchange (Larcher, 1975). A curious alternative exists for using N₂ as a pressurizing gas, where some of the N₂ might be produced through bacterial denitrification. Assuming the plant production system is not sterile, microflora that colonize the plant roots might be used to generate N₂ gas from nitrate (Garland, 1994). These “denitrifying” organisms can use nitrate as a terminal electron acceptor under anaerobic conditions, and in the process reduce the nitrate through N₂O to N₂ (Smart et al., 1996). This approach would require anaerobic zones or pockets in the root zone, and a supply of nitrate salts to meet the nitrogen needs of the plants and bacteria; in addition, the plants would have to be tolerant of hypoxic root environments (e.g., flood-tolerant species, such as rice). Clearly the kinetics and management of such an approach would need study, but the concept would fit well with low O₂ partial pressure systems where denitrification may be unavoidable.

Conclusions

Use of low-pressure enclosures for growing plants on Mars could reduce the structural requirements and gas leakage, and increase the potential for finding satisfactory transparent materials. This would require assessing plant responses to different combinations (partial pressures) of O₂, H₂O, and CO₂. In addition, the effects of total pressure and choices for pressurizing gases would need to be studied. The pressurizing gas would likely represent largest leakage loss from the system and costs could be reduced if this gas were obtained locally, i.e., the Martian atmosphere. Because CO₂ is relatively plentiful on Mars, CO₂ might be used as a pressurizing gas in addition to sustaining photosynthesis. But results from plant studies using very high CO₂ partial pressures (e.g., > 0.5 kPa) indicate that CO₂ might become injurious and/or

increase water demands in some species. Further studies are needed to define these CO₂ responses and to begin selecting or genetically engineering plants to perform well in low total pressure, high CO₂ partial pressure environments.

References

1. Andre, M. and Ch. Richaud. 1985. Can plants grow in a quasi-vacuum? In: R.D. MacElroy, M.V. Martello, and D.T. Smernoff (eds.) CELSS '85 Workshop. *NASA Technical Memorandum* 88215. NASA Ames Research Center, Moffett Field, CA.
2. Berkel N. van. 1984. Injurious effects of high CO₂. *Acta Horticulturae* 162:101-112.
3. Bugbee B., B. Spanarkel, S. Johnson, O. Monje, and G. Koerner. 1994. CO₂ crop growth enhancement and toxicity in wheat and rice. *Advances in Space Research* 14(11):257-267.
4. Corey, K.A., D.J. Barta, and D.L. Henninger. 1997. Photosynthesis and respiration of a wheat stand at reduced atmospheric pressure and reduced oxygen. *Advances in Space Research* 20(10):1869-1877.
5. Daunicht, H. J. and H. J. Brinkjans. 1992. Gas exchange and growth of plants under reduced air pressure. *Advances in Space Research* 12(5):107-114.
6. Drake, B.G., M.A. Gonzalez-Meler, and S.P. Long. 1996. More efficient plants: A consequence of rising atmospheric CO₂? *Annual Reviews of Plant Physiology and Plant Molecular Biology*. 48:609-639.
7. Ehret D.L. and P.A. Jolliffe. 1985. Leaf injury to bean plants grown in carbon dioxide enriched atmospheres. *Canadian Journal of Botany* 63:2015-2020.
8. Gale, J. 1973. Experimental evidence for the effect of barometric pressure on photosynthesis and transpiration. In: *Plant Response to Climatic Factors*, Proc. Uppsala Symp. (1970).
9. Galston, A.W. 1992. Photosynthesis as a basis for life support on Earth and in space. *BioScience* 42:490-493.
10. Garland, J.L. 1994. The structure and function of microbial communities in recirculating hydroponic systems. *Advances in Space Research* 14:383-386.
11. Grotenhuis T.P. and B. Bugbee. 1997. Super-optimal CO₂ reduces seed yield but not vegetative growth in wheat. *Crop Science* 37:1215-1222.
12. Hicklenton P.R. 1988. *CO₂ enrichment in the greenhouse*. Timber Press, Portland, Oregon, USA.
13. Larcher, W. 1975. *Physiological plant ecology*. Springer-Verlag, Berlin.
14. Mackowiak, C.L., L.M. Ruffe, N.C. Yorio, and R.M. Wheeler. 1994. Effect of carbon dioxide enrichment of radish production using nutrient film technique (NFT). *NASA Technical Memorandum*, 109198. Kennedy Space Center, FL.
15. Mackowiak, C.L. and R.M. Wheeler. 1996. Growth and stomatal behavior of hydroponically culture potato (*Solanum tuberosum* L.) at elevated and super-elevated CO₂. *Journal of Plant Physiology* 149:205-210.
16. Marschner, H. 1995. *Mineral nutrition of higher plants. Principles of plant nutrition*. Academic Press, New York, NY, USA.
17. McKay, C.P. 1984. A short guide to Mars. In: P.J. Boston (ed.) *The eCas for Mars*. Vol 57, Science and Technology Series, Amer. Astronautical Soc., San Diego, CA.
18. Musgrave, M.E., W.A. Gerth, H. W. Scheld, and B.R. Strain. 1988. Growth and mitochondrial respiration of mungbeans (*Phaseolus aureus* Roxb.) germinated at low pressure. *Plant Physiology* 86:19-22.
19. Myers, J. 1954. Basic remarks on the use of plants as a biological gas exchangers in a closed system. *J. Aviation Med.* 25:407-411.
20. Tibbitts, T.W. and T.T. Kozlowski. 1979. *Controlled environment guidelines for plant research*. Academic Press, Inc. New York, NY, USA.

21. Schwartzkopf, S.H. and R.L. Mancinelli. 1991. Germination and growth of wheat in simulated Martian atmospheres. *Acta Astronautica* 25:245-247.
22. Siegel, S.M., L.a. Rosen, and C. Giunarro. 1963. Plants at sub-atmospheric oxygen-levels. *Nature* 198:1288-1290.
23. Smart, D., K. Ritchie, and B. Bugbee. 1996. Mass transfer in the biological fast lane: High CO₂ and a shallow root zone. *Life Support and Biosphere Science* 3:43-46.
24. Wheeler, R.M., C.L. Mackowiak, L.M. Siegrist, and J.C. Sager. 1993. Supraoptimal carbon dioxide effects on growth of soybean (*Glycine max* (L.) Merr.). *Journal of Plant Physiology* 142:173-178.
25. Wheeler, R.M., C.L. Mackowiak, N.C. Yorio, and J.C. Sager. 1999. Effects of CO₂ on stomatal conductance: Do stomata open at very high CO₂ concentrations? *Annals of Botany* 83:243-251.
26. Wittwer SH, Robb W.M. 1964. Carbon dioxide enrichment of greenhouse atmospheres for food crop production. *Economic Botany* 18:34-56.