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Martian base agriculture: The effect of low gravity on water flow, nutrient cycles, and microbial biomass dynamics

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Abstract

The latest advances in bioregenerative strategies for long-term life support in extraterrestrial outposts such as on Mars have indicated soil-based cropping as an effective approach for waste decomposition, carbon sequestration, oxygen production, and water biofiltration as compared to hydroponics and aeroponics cropping. However, it is still unknown if cropping using soil systems could be sustainable in a Martian greenhouse under a gravity of 0.38*g*. The most challenging aspects are linked to the gravity-induced soil water flow; because water is crucial in driving nutrient and oxygen transport in both liquid and gaseous phases, a gravitational acceleration lower than $g = 9.806\ \mathrm{m\ s^{-2}}$ could lead to suffocation of microorganisms and roots, with concomitant emissions of toxic gases. The effect of Martian gravity on soil processes was investigated using a highly mechanistic model previously tested for terrestrial crops that couples soil hydraulics and nutrient biogeochemistry. Net leaching of NO_3^- solute, gaseous fluxes of NH_3, CO_2, N_2O, NO and N_2, depth concentrations of O_2, CO_2 and dissolved organic carbon (DOC), and pH in the root zone were calculated for a bioregenerative cropping unit under gravitational acceleration of Earth and for its homologous on Mars, but under 0.38*g*. The two cropping units were treated with the same fertilizer type and rate, and with the same irrigation regime, but under different initial soil moisture content. Martian gravity reduced water and solute leaching by about 90% compared to Earth. This higher water holding capacity in soil under Martian gravity led to moisture content and nutrient concentrations that favoured the metabolism of various microbial functional groups, whose density increased by 5–10% on Mars as compared to Earth. Denitrification rates became substantially more important than on Earth and ultimately resulted in 60%, 200% and 1200% higher emissions of NO, N_2O and N_2 gases, respectively. Similarly, O_2 and DOC were consumed more rapidly in the Martian soil and resulted in about 10% increase in CO_2 emissions. More generally, Martian cropping would require 90% less water for irrigation than on Earth, being therefore favourable for water recycling treatment; in addition, a substantially lower nutrient supply from external sources such as fertilizers would not compromise nutrient delivery to soil microorganisms, but would reduce the large N gas emissions observed in this study.

Keywords: Martian agriculture; Space agriculture; Life support system; Microgravity and hypogravity; Soil biogeochemistry

1. Introduction

Mars represents the ultimate challenge for agriculture experimentation and technology aimed at supporting long-term life support of humans in extraterrestrial outposts. In the hypothesis that Mars can be inhabited by a six-people crew by 2050 (Yamashita et al., 2006) or earlier 2030 (Schrope, 2010), soil-based agriculture is being considered as a bioregenerative strategy to recycle water, produce food, sequester carbon dioxide (CO_2) while producing oxygen (O_2), and decomposing organic wastes (e.g., Salisbury, 1992; Yamashita et al., 2006). However, Mars gravitational acceleration (0.38*g* with $g = 9.806\ \mathrm{m\ s^{-2}}$), air pressure (less than 1% the Earth's one), atmosphere composition (about 95.3% CO_2, 2.7% dinitrogen (N_2), 1.6% argon, and only 0.13% O_2), extremely cold and variable temperature (ranging between about −150 and

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+20 °C), and low solar radiations (approximately 40% less than on Earth) represent limiting conditions for agriculture as it is practiced on Earth.

Hydroponics and aeroponics techniques, which use nutrient solutions in a bath and as aerosols, respectively, were investigated in the past decades (e.g., Hoagland and Arnon, 1950) and have been proven successful to sustain crop production for relatively long time periods. Because hydroponics and aeroponics do not use soil, they are highly advantageous in terms of weight-reduction on spacecrafts or orbiting space stations, in addition to the fact that they can be highly automated to control nutrient and water dosage. The most important cropping experiments in microgravity were performed in the early 90s onboard the MIR Soviet station using porous media in phytotron cells, where a capillary-driven water delivery system was designed to feed plants. The choice of using a porous matrix rather than a hydroponic or aeroponic system was motivated by the possibility to entrap water by capillary forces within a medium in contrast to having free water in the absence of gravity. Besides the use of porous material to constrain the free movement of water, Nelson et al. (2008) have further indicated that Earth-like soil media would carry more beneficial effects on a Martian station. In fact, soil microbial communities can metabolize most compounds of potential toxicity and mineralize organic matter whereas hydroponic and aeroponic systems lose these capabilities because of the absence of microorganisms. Additionally, soil systems offer a sustainable waste recycling strategy to recover water and nutrients through systems such as constructed wetlands, bio- and phyto-filtration systems (Silverstone et al., 2003; Nelson et al., 2008), and composting (Finstein et al., 1999a, 1999b; Kanazawa et al., 2008; Wheeler, 2003). Overall, soil-based cropping and composting involve natural processes that offer compactness, low energy demand, near-ambient reactor temperatures and pressure, reliability, forgiveness of operational errors or neglect (Finstein et al., 1999a; Nelson et al., 2008). Large uncertainties for the success of Martian base agriculture, however, lie in the response of plant growth and nutrient cycling to low gravity, in the potential use of Martian soils as an *in-situ* resource and in the way human by-products and inedible composted biomass would interact with off-planet soil materials.

In the perspective of practicing soil-based cropping in a Martian greenhouse, the atmosphere pressure, composition, and temperature, as well as convection in the greenhouse environment can presumably be controlled with a narrow range of uncertainty, whereas gravity cannot be controlled. Hence, the most important aspect requiring a careful analysis is how low gravity could affect soil physical and biogeochemical processes (e.g., Monje et al., 2003; Silverstone et al., 2003; Porterfield, 2002). Because of Mars' lower gravitational acceleration than the Earth's one, convective gas mixing would be weaker and could easily be suppressed by viscous flows (Yamashita et al., 2006). Therefore, gas convection around plant leaves could substantially decrease compared to a situation on Earth, thereby reducing the evaporation rate (Monje et al., 2003; Hirai and Kitaya, 2009) with possible repercussions on O_2 and CO_2 exchange rates. Alteration of gas and nutrient exchange rates could be the cause of the uneven and unhealthy plant growth experimentally observed by Hoson et al. (2000) in phytotron chambers under microgravity.

In the soil root zone, adequate supply of water, nutrients and O_2 is required for plants and microorganisms' metabolism, and consequently for organic matter mineralization (e.g., Salisbury, 1992; Monje et al., 2003). The rate at which nutrients become available to roots and microorganisms is principally determined by the soil texture and structure (e.g., porosity), the soil hydraulic properties (e.g., permeability), the soil moisture content, and the water flow rate within the medium. Water, solutes and gases move through the soil by advective and diffusive flows but whereas diffusion is not susceptible to gravity (i.e., it can be described as temperature-dependent Brownian motion) advection on Mars would be substantially different as compared to advection on Earth, and would result in a net change in nutrient dispersion and transport rate at the Darcy's scale. It has been observed that a lower gravity results in lower infiltration rate and longer water and solute residence time (e.g., Jones and Or, 1999; Heinse et al., 2007), but it is not clear whether this would hinder, maintain or facilitate nutrient accessibility for plants and soil microorganisms. From a theoretical viewpoint, pore wetting in reduced gravity would occur with a higher tendency for the water to distribute on the pore surface, thus potentially creating a liquid film on the surface of soil solid particles that could isolate air pockets (Jones and Or, 1999; Monje et al., 2003; Heinse et al., 2007). These air pockets would presumably reduce significantly the soil permeability and could entrap soluble nutrients and gaseous species that would consequently not be available to roots and microorganisms at the rates they would on Earth. In addition, experiments in microgravity have demonstrated that a transition in moisture content would dislocate particles by buoyancy, thus affecting the soil hydraulic properties in a dynamical way (Jones and Or, 1999).

For an effective and safe soil-based agriculture on Mars, we aim to address two aspects: the first is the effect of $0.38g$ gravity on water flow, and the second is the feedback that water flow may exert on the nutrient and biomass dynamics. Whereas concerns have been expressed on these aspects in qualitative terms and on water dynamics only (Monje et al., 2003; Silverstone et al., 2003; Porterfield, 2002; Heinse et al., 2007), we propose here an approach to quantitatively analyze the implications of low gravity on the coupled dynamics of soil hydraulics and biogeochemistry as a whole. To this end, a highly mechanistic model, TOUGHREACT-N (Maggi et al., 2008), was calibrated on experimental data from Earth and was used to predict the effects of Martian low gravity on the small-scale interplays between physical and biogeochemical feedbacks in a bioregenerative soil unit. Attention is devoted to water flow, rates of microbially-mediated biogeochemical reactions, and gaseous and leaching losses of nitrogen (N) and carbon (C) species. Finally, we discuss the implications of such findings for the short and long-term run of a hypothetical soil-based cropping system on Mars.

2. Methods

2.1. Bioregenerative crop unit

Several functioning schemes and technical designs have been proposed for space applications of bioregenerative cropping units (e.g., Hossner et al., 1991; Bingham et al., 2000), including recycling of water and nutrients to reduce system costs and to preserve water. Here, we have schematized a bioregenerative unit as an isolated chamber that receives water and nutrient from a recirculation system (Fig. 1) with the N-fertilizer supplied as NO_3^- in the same N-equivalent dose as in typical agricultural applications on Earth. Water and nutrient may arrive from other recycling/composting units not investigated in this instance, while we have envisioned that the leachate can be captured and send to the same recycling and recirculating units introduced above. The temperature, atmospheric total pressure, and partial pressures of N_2, CO_2 and O_2 gases were assumed to be maintained within the cropping unit at values found on Earth.

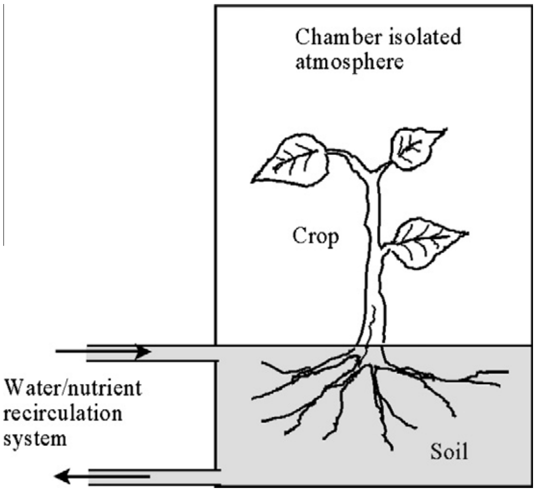

Fig. 1. Schematics of the bioregenerative soil-based cropping unit.

2.2. Model

The model used in this study is TOUGHREACT-N (Maggi et al., 2008; Gu et al., 2009), the most recently developed model based on the family of multiphase and multicomponent reaction–advection–diffusion models TOUGH2 and TOUGHREACT (Pruess et al., 1999; Xu et al., 2005, 2006; Xu, 2008). TOUGHREACT-N describes soil moisture dynamics, the nitrogen (N) cycle, dissolved organic carbon (DOC) dynamics, numerous chemical and biogeochemical kinetic and equilibrium reactions involved in the N and C cycles, and the dynamics of various microorganism functional groups.

The N cycle in TOUGHREACT-N includes biological nitrification and denitrification reaction chains, and chemical denitrification along various pathways (Fig. 2, Maggi et al., 2008). Nitrification was modeled using two oxidation reactions mediated respectively by ammonia-oxidizing autotrophic bacteria (AOB) and by nitrite-oxidizing autotrophic bacteria (NOB) along the sequence $NH_4^+ \rightarrow NO_2^- \rightarrow NO_3^-$ (e.g., Salsac et al., 1987). AOBs and NOBs are active in moist soils under oxic conditions, but become inactive at low soil moisture content and water potential, and under anoxic conditions (e.g., Rosswall, 1982). In these conditions, nitrification can be performed by heterotrophic nitrifying microorganisms (*i.e.*, some fungi and bacteria, Prosser, 1989). However, their biological functioning is not well understood yet and, since the soil conditions under investigation are favourable to AOB and NOB, we neglected heterotrophic nitrification. Denitrification was modeled through the sequence of redox reactions $NO_3^- \rightarrow NO_2^- \rightarrow NO \rightarrow N_2O \rightarrow N_2$ mediated by facultative anaerobic heterotrophic denitrifying bacteria (DEN) that oxidize dissolved organic carbon (DOC) to CO_2 (i.e., Knowles, 1982). The metabolism of DEN is favoured in anoxic conditions but it declines under water drought stress. Some AOBs are capable of carrying out part of the denitrification reactions in anoxic conditions as DEN

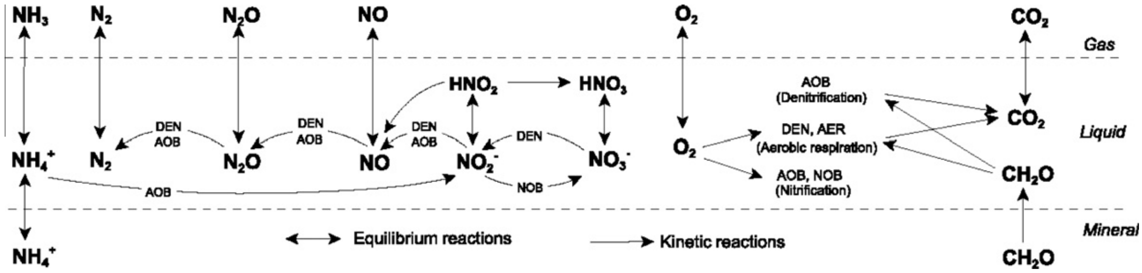

Fig. 2. Representation of the nitrification and denitrification reactions (left side) and microbial respiration reactions (right side) introduced in TOUGHREACT-N. Mineral, liquid, and gaseous domains are separated by dashed lines. AOB, NOB, DEN, and AER stand for ammonia-oxidizing bacteria, nitrite-oxidizing bacteria, denitrifying bacteria, and aerobic bacteria, respectively. CH_2O is the carbohydrate C source in anaerobic DEN respiration.

microorganisms (e.g., Wrage et al., 2001), pathway taken into account in TOUGHREACT-N. Chemical denitrification of HNO_2^- into HNO_3^- and NO was also taken into account (i.e., $NO_2^- \leftrightarrow HNO_2^- \rightarrow HNO_3^- \leftrightarrow NO_3^-$, and $HNO_2^- \rightarrow NO$, Venterea and Rolston, 2000a). Oxidation of NO into NO_2^- by heterotrophic and autotrophic bacteria (e.g., Dunfield and Knowles, 1997; Venterea and Rolston, 2000a, 2000b) was not taken into account explicitly, but was lumped into the denitrification rates. We did not include N_2 fixation because it mainly occurs by symbiosis between legumes and diazotrophs. Dissimilatory nitrate reduction to ammonium was not taken into account explicitly.

In linking the N and C cycles in a simplified manner, we assumed that a background organic carbon dissolution sustains a DOC pool of CH_2O carbohydrate (e.g., Chen and MacQuarrie, 2004; Li et al., 1992). DOC is competitively consumed by AOB and DEN during denitrification, and by other heterotrophic and aerobic microorganisms (AER) during aerobic respiration, resulting in CO_2 production (Fig. 2).

The dynamics of the microbial functional groups considered here were modeled taking into account the effect of electron donor, acceptor and inhibitor concentrations through Monod kinetics, while the effect of temperature, pH, and water content on microbial biomass growth rate was modeled using piece-wise linear functions (Boon and Laundelot, 1962; Skopp et al., 1990; Maggi and Porporato, 2007).

2.3. Experimental data

The physical and biochemical parameters used in TOUGHREACT-N were calibrated on data collected from a furrow irrigated tomato field during the period July–August 1998 in western Sacramento County, California (Venterea and Rolston, 2000a, 2000b). The choice of tomatoes was driven by the availability of a rich data set with high spatial and temporal resolution for several control variables in the soil. A precision fertilization technique was practiced by injecting 12 g m^{-2} of anhydrous ammonia (NH_3) at 5 cm depth along bands of 15 cm width separated by 85 cm. Irrigation started 9 d later and ended on day 14. Soil water saturation S_θ, pH, concentrations of NH_4^+, NO_2^-, and NO_3^- in the depth intervals 0–5 and 5–10 cm, and NO, N_2O, and CO_2 gas fluxes were recorded for 20 d after fertilization before development of seedling, when the effect of root on water and nutrient uptake as well as on soil properties were relatively limited (Venterea and Rolston, 2000a, 2000b).

3. Results

3.1. Calibration on terrestrial data

TOUGHREACT-N was calibrated using data from the Earth tomato field (Section 2.1) for a one-dimensional 60 cm long soil column with a spatial resolution of 1.25 cm. Fertilization was modeled in TOUGHREACT-N as an upscaled uniform concentration of 96 g NH_3 m^{-2} (0.12 mol L^{-1} N) in the top 10 cm of the soil column on day 0. Irrigation consisted of one 24 h event at a rate of 8.64 L H_2O m^{-2} d^{-1} on day 9 followed by a second 96 h irrigation event at a rate of 34.6 L H_2O m^{-2} d^{-1} from day 10 to day 14. Evaporation from the soil surface was not measured but was assumed to be in the order of magnitude of 2 L m^{-2} d^{-1} (Maggi et al., 2008). The validation of TOUGHREACT-N with the parameters so obtained was performed with data from agricultural fields under various fertilization and irrigation managements in France (Gu et al., 2009) and demonstrated its robustness to mechanistically capture the relevant water and nutrient dynamics in a variety of agricultural settings.

3.2. Simulations of the bioregenerative soil system under terrestrial and Martian gravity

The parameters calibrated on the terrestrial plot were subsequently used to simulate a 30 cm deep soil bioregenerative unit exposed to the terrestrial and Martian gravitational acceleration (1*g* and 0.38*g*, respectively). For the Martian system, we have considered a soil substrate with identical textural properties, structure, porosity and organic matter content as on Earth (silt loam), but we have imposed a lower soil permeability than on Earth. Although the permeability is not a function of the gravitation, an acceleration of 0.38*g* produces a three times higher capillary rise than under 1*g* that can isolate air pockets and reduce the unsaturated soil hydraulic conductivity. In order to take into account this effect, we have described the Martian soil using an apparent permeability equal to 0.38 the soil permeability on Earth (i.e., 0.69×10^{-13} m^2 versus 1.82×10^{-13} m^2). This is a rough estimate that serves, however, as an initial seed to investigate the possible effects of low gravity on water flows and nutrient cycling at the Darcy's scale.

All initial conditions (i.e., solute and gaseous concentrations, microorganism densities, and pH) and boundary conditions (i.e., irrigation and evaporation) used to describe the Martian soil unit were identical with those on Earth, except for the initial soil water saturation, S_θ, which was set to 0.45 on Mars (0.95 was used on Earth) to maintain similar average soil moisture contents in the two planets during the 20 d test time. Both terrestrial and Martian bioregenerative units were fertilized with a dose of 350 g NO_3^- m^{-2}, which is equivalent to 96 g NH_3 m^{-2} used in the terrestrial tomato field.

Although the bioregenerative cropping unit depicted in Fig. 1 foresees a water and nutrient recirculation system, the unit ecodynamics was simulated here over a 20-d time frame that did not directly involved recirculation and underwent only one irrigation application. However, the water leaching rate at the base of the unit represents the volume of water that is addressed to a recirculation unit. A study aimed at investigating the long-term response of the unit should however introduce a recirculation input that takes into account the water flow rate and the concentrations of nutrients in the recycled water.

The model outcomes from the terrestrial and Martian bioregenerative units are compared and analysed in the following sections.

3.3. Soil moisture dynamics, pH, and N solute concentrations

The soil water saturation S_θ on Mars decreased over time much more slowly than on Earth and remained at relatively higher values after day 4 even if its initial value was about half the one on Earth (0.45 versus 0.95, Fig. 3a). The water holding capacity was consequently very different in the two planets; an irrigation event produced a saturation $S_\theta \approx 0.50$ around day 13 on Mars, compared to a saturation of $S_\theta \approx 0.38$ on Earth. Such higher saturation during free drainage and infiltration of a water front is explained by reduced (gravitational) advection and diffusion rates.

The temporal evolution of the pH on Mars substantially differed from the one on Earth after day 4, being consistently lower than on Earth by about 1–2 pH units (Fig. 3*b*).

NH_4^+ and NO_2^- ions were not monitored in these simulations as N nutrient was not supplied as NH_4^+ but as NO_3^- fertilizers. Consequently, nitrification was relevant only to the extent to which AOB functional group nitrified a background NH_4^+ production while simultaneously participating in the denitrification reactions (Fig. 2). Because NO_3^- production rate was substantially smaller than the NO_3^- input from fertilization, its concentration persistently decreased over time both on Earth and Mars (Fig. 3c). However, NO_3^- concentration on Mars did not undergo a steep depletion during the first 4 d as observed on Earth, and remained about 100% constantly higher than on Earth after day 4, when the rate of NO_3^- depletion was not substantially different in the two planets (Fig. 3c).

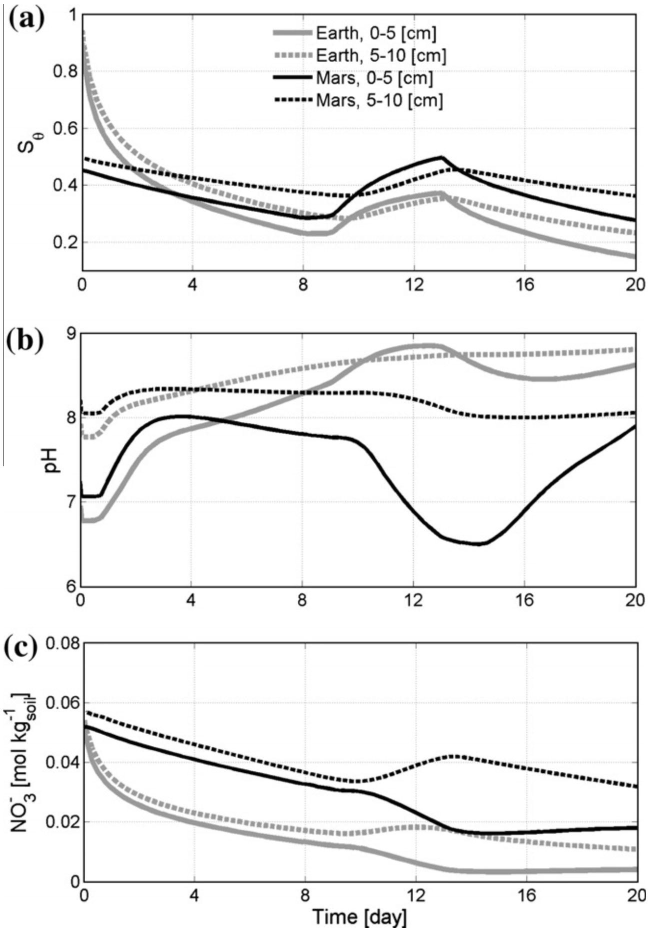

Fig. 3. Time evolution of the soil saturation S_θ (a), pH (b), and nitrate ion NO_3^- concentration (c) on Earth (gray lines) and on Mars (black lines) calculated using TOUGHREACT-N for depth intervals 0–5 (solid lines) and 5–10 cm (dotted lines) on Earth (gray) and on Mars (black).

3.4. Water, solute and gaseous losses

The cumulative water volume leaching from the unit was about 90% lower on Mars than on Earth over the 20-d simulation period (Fig. 4). Similarly, leaching of NO_3^- was more than 90% lower on Mars compared to on Earth and can be ascribed to the sensibly lower water leaching rate (Fig. 4). However, it has to be noticed that this particularly low water flow rate did not result in an increased solutes' residence time in the root zone; in fact, the NO_3^- concentration was higher on Mars but decreased at about the same rate as on Earth, thus signifying that the NO_3^- turnover time on the two planets was nearly the same. These dynamics indicate that the lower leaching rate on Mars was counterbalanced by a larger NO_3^- consumption through denitrification. In addition to influencing solute concentrations, the Martian gravity of 0.38*g* had important repercussions on gas emissions over time (Fig. 5) and caused NO, N_2O, and N_2 cumulative gas emissions on Mars to exceed the ones on Earth by 60%, 200% and 1200%, respectively, whereas CO_2 cumulative fluxes increased by about 10% (Fig. 4).

3.5. Vertical distribution of microbial functional groups

We have excluded from this analysis the AOB and NOB functional groups as their respective substrates NH_4^+ and NO_2^- were absent from the systems. The difference in water and nitrogen losses in the Martian unit compared to the terrestrial soil suggest that low gravity would affect the dynamics of the various soil microbial functional groups. The time evolution of the vertical profiles of AER and DEN groups evolved on Mars toward a stratification similar to as on Earth, that is, with oxidizing AER microorganisms mainly located in the top 10 cm of the soil (Fig. 6a and b), and anaerobic denitrifying microorganisms at lower depth (Fig. 6c and d). However, relatively higher microbial biomass was found on Mars, with average concentration about 5–10 times higher than on Earth.

3.6. Soil respiration

The higher biomass of the microbial functional groups in the Martian soil had repercussions on soil respiration. A

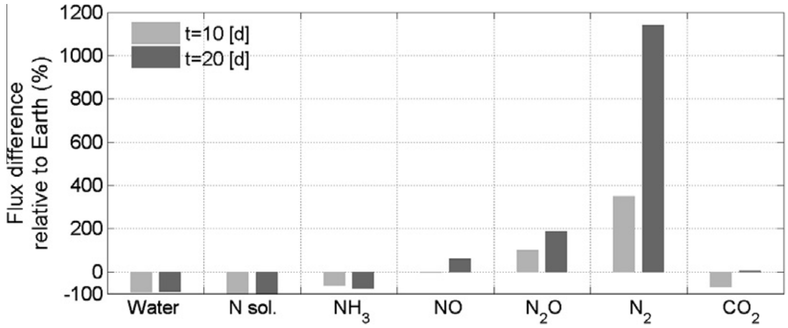

Fig. 4. Difference relative to Earth of the time cumulative fluxes of water and N solutes (mainly NO_3^- and traces of NH_4^+, NO_2^-) from 30 cm depth, and of NH_3, NO, N_2O, N_2 and CO_2 gas emissions from the surface. The relative differences are expressed in percent (%).

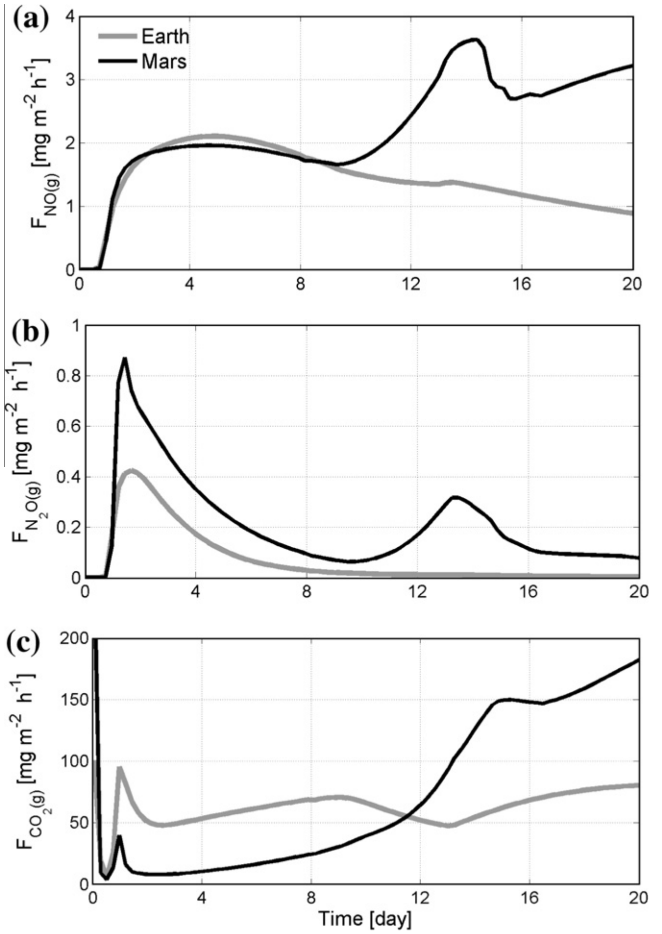

Fig. 5. Gaseous emissions over time of NO (a), N_2O (b), CO_2 (c) calculated on Earth (gray lines) and on Mars (black).

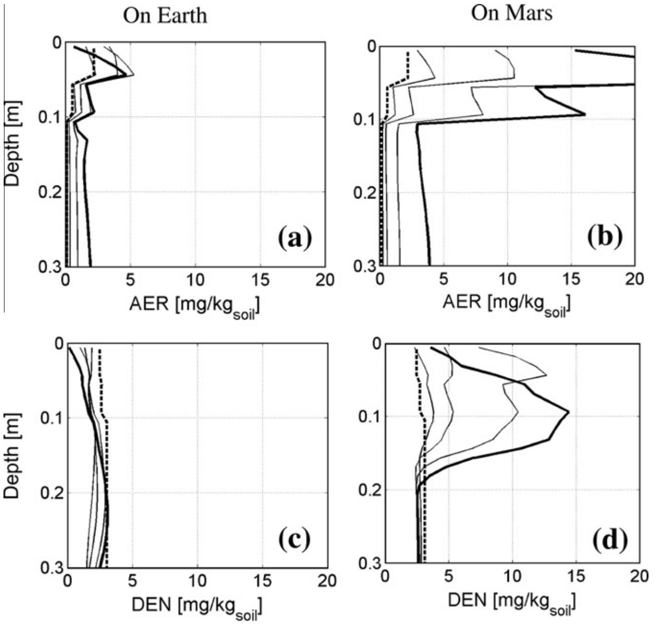

Fig. 6. Time evolution of the vertical concentration of aerobic bacteria (AER, top panels a and b) and denitrifying bacteria (DEN, bottom panels c and d) on Earth (left panels) and on Mars (right panels).

comparison of the vertical O_2 partial pressure at intermediate times shows that O_2 consumption was more important on Mars over the whole profile (Fig. 7a and b). This higher O_2 consumption on Mars was accompanied by higher consumption of dissolved organic carbon (DOC), whose concentration became lower on Mars than on Earth in the top 10 cm (Fig. 7c and d). It has to be noticed, however, that DOC concentration on Earth decreased more than on Mars below 10 cm depth due to higher leaching rate. The high O_2 and DOC consumption rates observed in the Martian soil resulted in a higher CO_2 production rate, leading to CO_2 partial pressure about 100% higher than on Earth (Fig. 7e and f), thus explaining the higher rates of NO, N_2O, N_2 and CO_2 gas emissions from the unit on Mars.

4. Discussion

The differences in biogeochemical dynamics observed in the Martian and terrestrial root zones were exclusively dictated by the effect of low Martian gravity (0.38*g*) on water advection and diffusion with respect to the gravity on Earth (1*g*), which conditioned nutrient transport and delivery to microorganisms. Two main features arise from this study in relation to nutrient cycling and microbial biomass dynamics.

First, we observed that the temporal pattern of NO_3^- concentrations was very similar in soils on Mars and on the Earth even if the concentrations on Mars were

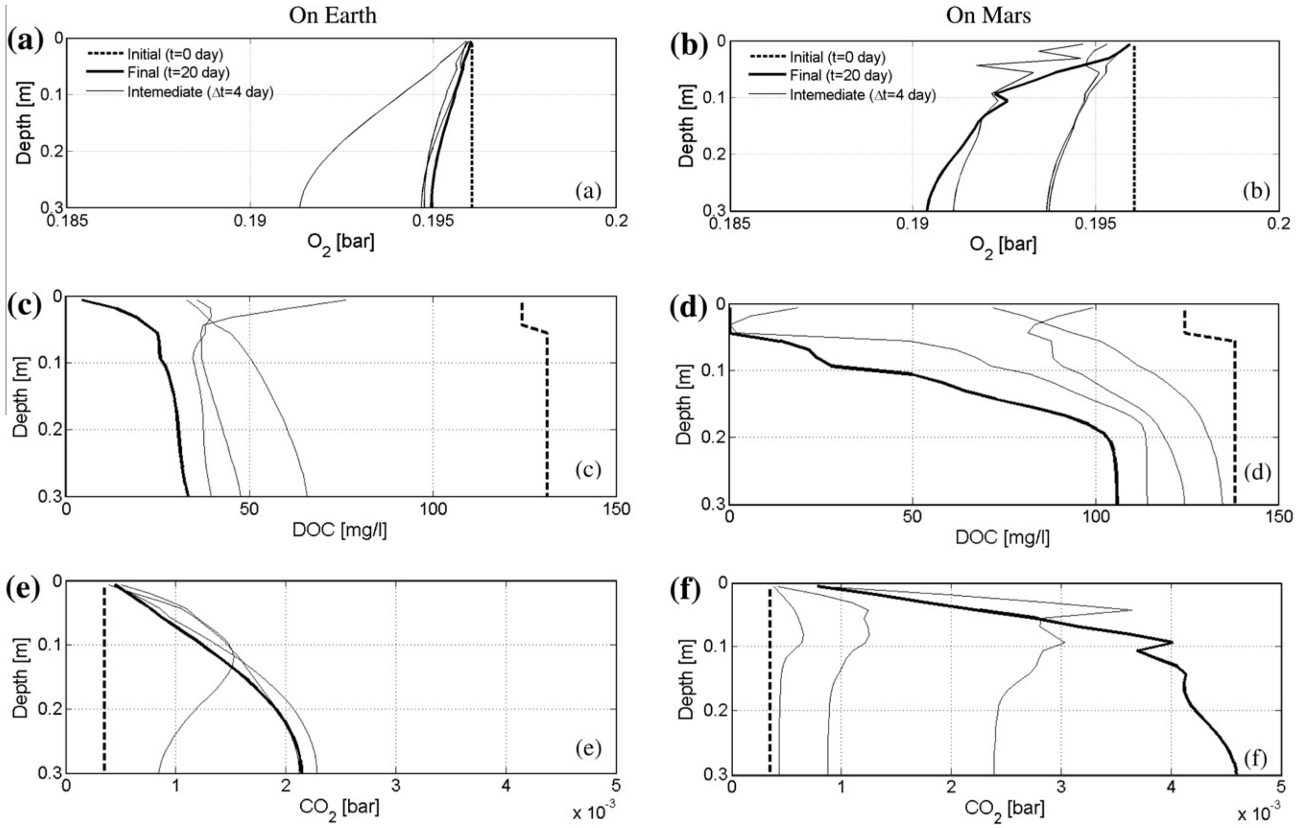

Fig. 7. Time evolution of the vertical concentration of O_2 partial pressure (panels a and b), DOC concentration (panels c and d) and CO_2 partial pressure (panels e and f) on Earth (left panels) and on Mars (right panels).

relatively higher. This higher concentration could be ascribed to about 90% lower water leaching rates, which led to more than 90% decrease in NO_3^- solute transport and loss by leaching. However, it is important to note that lower N solute leaching did not imply a higher residence time in the Martian root zone. Rather, the NO_3^- turnover time was very similar within the soils of the two planets. This result can only be explained as due to higher gaseous losses from the unit on Mars. Ultimately, these higher gaseous emissions on Mars principally occurred because of a lower NO_3^- leaching, which resulted in higher N availability to denitrifying microorganisms (DEN) and higher production rate of NO, N_2O, and N_2 gases. The DEN group was also responsible for a higher DOC consumption, and higher CO_2 production by respiration. These circumstances allowed the DEN functional group to grow more effectively than on Earth and achieve a biomass concentration 5–10 times higher.

Second, our results clearly highlight that a lower gravity such as encountered on Mars would lead to lower water and nutrient leaching in soil, but would also result in much higher gaseous emissions. The major reason for these gravity-induced effects on Mars is the slower soil moisture and nutrient depletion over time, which would expose the microorganisms to more favourable conditions of moisture content (always between optimal values around $S_0 = 0.5$) and nutrient concentration, thereby making possible for the microbial functional groups studied here to grow faster than on Earth. The results proposed here show how important the effect of low gravity on water availability and nutrient delivery is in relation to the microorganism dynamics. A comprehensive analysis of the nutrient and biomass inventories, and of the leaching and gaseous emission rates within a soil-based cropping unit has been addressed for the gravitational acceleration of Earth ($g = 9.806\ \mathrm{m\ s^{-2}}$), Mars ($0.38g$), the Moon ($0.16g$) and in an orbiting space station ($0g$), showing that the leaching rates decreases substantially for a gravitational acceleration lower than g, while the gaseous emissions increase more or less linearly with g decreasing (Maggi and Pallud, 2010).

These results suggest that a lower gravity may not jeopardize the biogeochemical properties of the soil and its cropping potential. Rather, Martian cropping appears to have a lower water and nutrient footprint than agriculture normally practiced on Earth. Agriculture on Mars would require about 90% less water. In addition, because it is hypothesized that the bioregenerative cropping unit would be coupled to a water recirculation system, this lower water footprint implies a substantially longer water turnover time, feature which can have positive implications on the effectiveness of the water recycling system. In a similar way, because nutrient leaching is much lower than on Earth, a substantially lower net mineral N supply (−40%

to −70%) would allow for nutrient delivery to the soil microorganisms on Mars equally effectively as on Earth. A reduction of mineral N supply from external sources such as fertilizers would also reduce the emissions of NO, N_2O, N_2, and CO_2 gases within the cropping unit. This aspect is very important for the equilibrium of the atmosphere within a hypothetical Martian greenhouse, which could suffer from rapid accumulation of toxicant gases (NO, N_2O, and CO_2).

In addition to the aspects discussed above, issues concerning the use of Martian soil as a local resource have to be clarified in the perspective to maintain the long-term health of the cropping unit. The hypothesis to use Martian soil as a local resource opens one of the largest uncertainty. The physical and chemical characteristics of Martian rocks and soils have been investigated by successive NASA rovers that carry a suite of state-of-the-art tools, such as various cameras, rock abrasion tool, and various spectrometers. However, it is not known how the organic material obtained through waste recycling and composting would interact with the Martian minerals. The use of Martian soil as growth medium would require treatment to remove potential toxicants, fill in deficiency for some nutrients, and prepare the mineral to host the complex fabric of diverse microorganisms that would make the soil a healthy substrate for plant growth. Recent literature on bioregenerative cropping units for space application does not seem to indicate Martian regolith as the primary growing medium because of the low aeration potential and the possible presence of toxicants (Salisbury, 1992). It is more likely that initial bioregenerative units would base their functioning on a rebuilt mineral porous matrix where water delivery is capillary-driven as in the experiments on the MIR station (Ivanova et al., 1993).

Soil-based agriculture on Mars would require a source of nutrients. Whereas this could be made available from recycling human wastes and inedible parts of plants that are composted, fertilization could be required, perhaps for a limited amount of time before a self-sustainable nutrient cycle can be established in a Martian greenhouse or cropping unit. The use of fertilizer would therefore produce dynamics highly resembling our observations and simulations. The response of the system to fertilizers would be characterized by small leaching rates, but would also be characterized by higher gas emissions.

Although we focused this work on the nitrogen nutrient, it is important to direct further research on the biogeochemical cycling of other macro-nutrients essential for plants such as phosphorous (P), sulphur (S), potassium (K), magnesium (Mg), and calcium (Ca), and micro-nutrients such as iron (Fe), manganese (Mn), zinc (Zn), copper (Cu), boron (B), molybdenum (Mo) and chlorine (Cl), which all play a crucial role to sustain plant life (Hossner et al., 1991).

Finally, it is not known if microorganisms inhabiting soils on Earth could adapt to the low Martian gravity, if low gravity could alter their life cycle, and if a soil system would be reliable on the long-term. Salisbury (1992) has expressed concern about possible catastrophic failures of a bioregenerative unit due to diseases of plants, human or animal. Epidemiological aspects in microgravity and in a limited environment have not been under the attention of the latest developments of bioregenerative space units, and will require careful consideration.

5. Conclusions

We have analysed the effects of low gravity on the hydraulic and biogeochemical processes taking place in soils for potential applications in Martian base agriculture. Mars was considered as an example where low-gravity agriculture could raise important and challenging aspects in that concern with the soil, water, nutrient and biomass interactions. Using a mechanistic model of soil hydraulics and biogeochemistry under low gravity, we have given evidence that (i) water infiltration rate substantially decreased, leading to about 90% lower water and nutrient loss by leaching, and to a substantially longer turnover time for a possible water recycling unit; (ii) relative to Earth, N gas emissions increased substantially for NO (+60%), N_2O (+200%) and N_2 (+1200%), while CO_2 emissions increased by 10%; (iii) the overall turnover time of N solutes within the root zone was not substantially affected, since the N inventory showed similar depletion rates on Earth and Mars; (iv) the nutrient application rate in a Martian cropping unit could be retained to substantially lower levels as compared to Earth as a consequence of lower leaching rates; (v) the microbial functional groups were located in similar soil depth intervals on Earth and Mars, but their biomass on Mars was 5–12 times higher than on Earth under terrestrial nutrient supply rates. These effects of low gravity on soil hydraulics, geochemistry and microbial dynamics would not compromise the biogeochemical properties of the soil and its cropping potential. However, we recognize that many aspects still have to be understood in low-gravity soil hydraulics (i.e., capillary processes) and biogeochemistry (nutrient sources and reliability on the long-term). This work represents the first attempt to quantitatively study low-gravity ecosystems using a highly mechanistic mathematical framework, but we hope to spur more attention on this topic.

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