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Space agriculture in micro- and hypo-gravity: A comparative study of soil hydraulics and biogeochemistry in a cropping unit on Earth, Mars, the Moon and the space station

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ABSTRACT

Increasing interest is developing towards soil-based agriculture as a long-term bioregenerative life support during space and planetary explorations. Contrary to hydroponics and aeroponics, soil-based cropping would offer an effective approach to sustain food and oxygen production, decompose organic wastes, sequester carbon dioxide, and filter water. However, the hydraulics and biogeochemical functioning of soil systems exposed to gravities lower than the Earth's are still unknown. Since gravity is crucial in driving water flow, hypogravity will affect nutrient and oxygen transport in the liquid and gaseous phases, and could lead to suffocation of microorganisms and roots, and emissions of toxic gases. A highly mechanistic model coupling soil hydraulics and nutrient biogeochemistry previously tested on soils on Earth ($g=9.806 \text{ m s}^{-2}$) is used to highlight the effects of gravity on the functioning of cropping units on Mars (0.38 g), the Moon (0.16 g), and in the international space station (ISS, nearly 0 g). For each scenario, we have compared the net leaching of water, the leaching of NH_3 , NH_4^+ , NO_2^- and NO_3^- solutes, the emissions of NH_3 , CO_2 , N_2O , NO and N_2 gases, the concentrations profiles of O_2 , CO_2 and dissolved organic carbon (DOC) in soil, the pH, and the dynamics of various microbial functional groups within the root zone against the same control variables in the soil under terrestrial gravity. The response of the soil ecodynamics was relatively linear; gravitational accelerations lower than the Earth's resulted in 90–100% lower water leaching rates, 95–100% lower nutrient leaching rates, and lower emissions of NH_3 and NO gases (80–95% and 30–40%, respectively). Lower N loss through leaching resulted in 60–100% higher concentration of the microbial biomass, but did not alter the vertical stratification of the microbial functional groups with respect to the stratification on Earth. However, the higher biomass concentration produced higher emissions of N_2O , N_2 , and CO_2 gases (80%, 200% and 40%, respectively).

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1. Introduction

Planetary and space exploration is experiencing a new golden era after the recent discovery of a significant amount of ice on the Moon (Hand, 2009) and the evidence of water found during the exploratory missions to Mars (e.g., Grotzinger, 2009). The National Aeronautics and Space Administration (NASA) and European Space Agency (ESA) envision supporting interplanetary missions targeting the man exploration of Mars (e.g. Mars500, ESA, 2009), the establishment of manned outposts on the Moon and, more generally, strengthening the International Space Station (ISS) capabilities to serve as a proxy for other operations (ISECG, 2007, 2010).

Within the sphere of feasibility and reliability assessment of long-term life support systems for these programs, growth of

plants to supplement the astronauts' diet has been under continuing investigation (e.g., Hossner et al., 1991; Yamashita et al., 2006). The crucial aspects are the system used to deliver water and nutrient to the roots, and the substrate upon which plants can grow. Various solutions have been tested to control water and nutrient delivery such as negative pressure control systems (Hoehn et al., 2000; Morrow et al., 1994) or active pumping control systems (Bingham et al., 2002; Heine et al., 2007). Small-scale experiments (e.g., LADA module, Bingham et al., 2002) have proven successful to grow small plants on a porous nutrient-enriched granular medium (Balkanine) in microgravity aboard the ISS, where water was injected and accumulated in a porous tube beneath the roots. Regardless of the specific delivery systems, predicting the moisture and nutrient movement through the root zone under microgravity has been shown relatively accurate if the exact properties of the porous material are known. A substantially smaller body of knowledge is currently available on how the rooting zone would perform in intermediate gravitational accelerations; this is

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hampered by the difficulty to reproduce hypogravity for relatively long time intervals and test the moisture and nutrient movement in porous materials.

Increasing attention is given to bioregenerative systems that explicitly consider real soils as growing media in place of artificial matrixes, porous tubes, membranes and other types of granular materials (e.g., Hossner et al., 1991; Salisbury, 1992; Hoenh et al., 2000; Silverstone et al., 2003, 2005; Nelson et al., 2008; Maggi and Pallud, 2010). For example, during planetary exploration, local minerals such as Lunar and Martian regoliths have been considered as growing substrates as well (Hossner et al., 1991; Hoffman and Kaplan, 1997; Silverstone et al., 2003; Hanford, 2004), although they probably would require specific physical, chemical and biological treatment before they can be used. Earth-like soils are therefore not excluded *a priori* as growing media in micro- and hypogravity environments but, rather, are an alternative to other constructed rooting zones. The advantage of bioregenerative soil-based systems is that they provide a self-sustainable microcosm that potentially offers compactness, low energy demand, near-ambient reactor temperatures and pressure, reliability, forgiveness of operational errors or neglect (Finstein et al., 1999), and a rich biodiversity of microorganisms (e.g., Nelson et al., 2008), all features that are being recognized only in the recent years as fundamental for the long-term sustainability of a life support system in space.

The first attempts to investigate the self-sustainability of agricultural microcosms materially isolated from the external environment (such as in the BIOS-3 and Biosphere2 experiments running in the last thirty years) were mainly focused on assessing the minimal ecosystem resources capable of sustaining food for a small crew. Since then, cropping systems designed for space applications have been investigated not only to secure food production, but also for O₂ production, CO₂ sequestration, organic waste composting, and water filtration (Finstein et al., 1999; Wheeler, 2003; Silverstone et al., 2003; Yamashita et al., 2006; Nelson et al., 2008). Optimized resources management has increased the efficiency of soil-based cropping systems in confined greenhouses, and has brought evidence that a crew can be sustained in isolation at healthy levels over relatively long time periods (Kanazawa et al., 2008; Aydogan-Cremaschi et al., 2009). However, the state-of-the-art research carried out on soil-based bioregenerative systems in space applications is limited to systems subject to the Earth's gravity. Robustness and reliability of soil systems in environments with different gravitational accelerations are currently far from being understood, and the effect of low-gravity on water flows is still as uncertain as its effect on nutrient transport and delivery to microorganisms. For example, the lower gravity of Mars (0.38 g), the Moon (0.16 g), and the ISS (variable near 0 g) represent challenging conditions for the physical and biogeochemical processes taking place in the root zone, where adequate supply of water, nutrients and oxygen is required for plants and microorganisms to function optimally (e.g., Podolsky and Mashinsky, 1994; Porterfield, 2002; Silverstone et al., 2003). The rate at which nutrients become available to roots and soil microorganisms is determined by advective and diffusive flows. Whereas diffusion is not directly susceptible to gravity, advection in micro- and hypogravity would substantially be affected (e.g., Scovazzo et al., 2001; Heitse et al., 2007). For ecosystems in hypogravity, challenging questions naturally arise regarding soil hydraulics, nutrient biogeochemistry, and microbial dynamics in the root zone: How would water and nutrient cycling in soils be affected by a gravity lower than on Earth? Would oxygen and nutrient delivery to plants and soil microorganisms be secured? Will the ecodynamics response be linear with decreasing gravity or will it become unstable? Finally, can soil-based bioregenerative systems be sustainable in terms of microbial biomass dynamics?

Part of the chemical and biochemical reactions of concern within a soil-based bioregenerative life support system have been investigated earlier (e.g., Volk and Rummel, 1987; Wheeler, 2003) but have not been implemented within a framework that also includes the physical (time-space), hydraulic, and biogeochemical processes within the soil root zone as a whole. In the attempt to fill these gaps, we have assessed the impact of gravitational accelerations lower than the Earth's on water flow, nitrogen (N) and carbon (C) biogeochemistry, and biomass dynamics by comparing several control variables in a soil-based cropping unit under the gravitational acceleration of Earth ($g=9.806 \text{ m s}^{-2}$), Mars (0.38 g), the Moon (0.16 g), and in an orbiting space station (nearly 0g). To this end, a highly mechanistic reactive transport model has been used for each of the four scenarios to calculate the net leaching of NH₃(aq), NH₄⁺, NO₂⁻ and NO₃⁻ solutes, the emissions of NH₃(g), CO₂, N₂O, NO and N₂ gases, the concentration profiles of O₂, CO₂ and dissolved organic carbon (DOC) over the soil root zone, of the pH, and of the concentration of nitrifying, denitrifying and aerobic heterotrophic microbial functional groups. Using these data, we have carried out a comparative analysis between the four gravity scenarios (i.e., Earth, Mars, the Moon, and the ISS). Here, we present a selection of our results and we discuss the implications of micro- and hypogravity on the short-term functioning of bioregenerative soil-based cropping units for space applications.

2. Methods

To assess the impact of gravity on a bioregenerative soil-based cropping unit we have used the general-purpose multiphase and multicomponent reaction-advection-diffusion model TOUGH-REACT (Pruess et al., 1999; Xu et al., 2005, 2006; Xu, 2008). It is used here to describe the soil moisture dynamics and various pathways of chemical and biogeochemical equilibrium and kinetic reactions involved in the C and N cycles, including the pH- and moisture-dependent dynamics of relevant microbial functional groups as described in Maggi et al. (2008). In earlier applications, TOUGHREACT has proven successful to capture in a mechanistic and robust way the multifaceted dynamics of N and C cycling in various soil systems (Gu et al., 2009; Gu and Riley, 2010).

2.1. Gravity-affected soil moisture dynamics

Under variable gravity conditions, soil moisture dynamics can be altered as a result of various physical processes. We have identified three effects. The first effect occurs at macroscopic scales in the vertical (gravitational) advection (Fig. 1a). The physics of this effect can be properly understood within the framework of the Richards equation as implemented in the TOUGH2/EOS9 module (Pruess et al., 1999)

$$\frac{\partial \theta}{\partial t} = \phi \frac{\partial S}{\partial t} = \frac{\partial}{\partial z} \left[k_r(S^*) \frac{k}{\mu} \frac{\partial}{\partial z} (p(S^*) + \rho g z) \right] \quad (1)$$

where θ is the soil moisture content, ϕ the soil porosity, S^* the soil water saturation ($0 \leq S^* \leq 1$), μ the water viscosity, k the absolute soil permeability, $k_r(S^*)$ the relative permeability expressed as a function of S^* ($0 \leq k_r(S^*) \leq 1$), and $p(S^*)$ the capillary pressure ($p < 0$ in unsaturated conditions) of a point at position z . Using the van Genuchten (1980) scaling, the relative permeability k_r and capillary pressures p are expressed as functions of the saturation S^* as

$$k_r(S^*) = (S^*)^{1/2} \left[1 - (1 - (S^*)^{1/m})^m \right]^2 \quad (2)$$

$$p(S^*) = -p_0 [(S^*)^{-1/m} - 1]^{1-m} \quad (3)$$

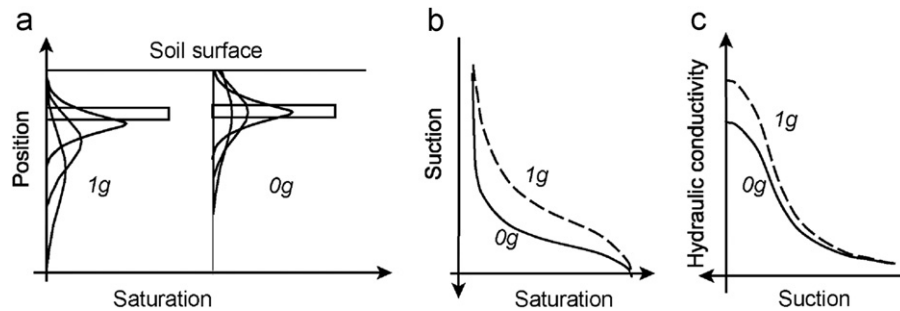


Fig. 1. Qualitative representation of the effect of gravity (a) on gravitational advection, (b) on the water retention characteristics, and (c) on permeability (hydraulic conductivity) due to air-pockets formation. These representations refer to 1 g and 0 g for simplicity whereas intermediate values of g will qualitatively produce intermediate effects.

where S^* is defined by the ratio

$$S^* = \frac{S - S_r}{S_m - S_r} \quad (4)$$

with $S = \theta/\phi$ the actual soil water saturation ($S_r \leq S \leq S_m$), S_r the irreducible hygroscopic water, S_m the maximum water saturation accounting for an irreducible gas volume within the soil matrix, and m and p_0 the empirical van Genuchten parameters. Eq. (1) shows that a decreasing value of g necessarily implies for the water flow to be increasingly driven by diffusion (proportional to the gradient $\partial p(S^*)/\partial z$) rather than advection (proportional to ρg). In the limit $g \rightarrow 0$ (Fig. 1a), the vertical water flow appears as a pure diffusive process (e.g., Scovazzo et al., 2001; Heinse et al., 2007). Capillary diffusion in a heterogeneous porous medium exposed to 0 g could result in preferential fingering patterns (Jones and Or, 1999). However, fingering will be neglected here under the assumption of uniform diffusion over the soil profile.

The second important effect of gravity on water flow is related to the alteration of the soil water retention curve (Fig. 1b), and hence on how $p(S^*)$ scales with the saturation S^* in Eq. (3). Measurements of the water retention curve of various granular materials during wetting and drainage showed that both m and p_0 decreased when g decreased from terrestrial to microgravity (Heinse et al., 2007). In antithesis with gravitational advection described earlier, this effect of gravity can be described only by empirical relations using the van Genuchten parameters of Eqs. (2) and (3). Possible physical explanations of this effect can be ascribed to local rearrangements of the particles and pore network geometry during wetting and drying, which could be more important in the absence of gravity than on Earth. Evidence that transient moisture would dislocate particles in microgravity has been reported by Jones and Or (1999), whereas Heinse et al. (2007) have also recorded slight changes in porosity. Gravity-induced effects on the water retention curve will be taken into account with empirical relationships describing changes in m and p_0 as functions of g , whereas the effect of gravity on soil porosity has not been included.

A third, potentially important effect of hypogravity on water flow in soils has been hypothesised to take place during pore wetting, which would occur with a higher tendency for the water to distribute on the pore surface because of the water surface tension. The resulting liquid film on particles' surface can isolate air pockets (Jones and Or, 1999; Monje et al., 2003; Heinse et al., 2007), reduce the soil permeability and hydraulic conductivity (Fig. 1c), and entrap soluble nutrients and gaseous species that would consequently not be available to roots and microorganisms at the rates they would on Earth (Bingham et al., 2000). Formation of air pockets in variable gravity has not been investigated in detail yet, and there exists no exhaustive physical understanding that could allow for a mechanistic modeling. Within this work, air

pocket-entrapment will parametrically be taken into account by decreasing the liquid saturation S_m in Eq. (2) for decreasing gravity.

2.2. Gravity-affected transport in the liquid and gaseous phases

Transport of chemical species is modeled by Fickian diffusion in the gas and liquid phases, and advection in the liquid phase. The rate of change of aqueous and gaseous concentrations C_{wi} and C_{gi} for each chemical species i are written as

$$\begin{aligned} \frac{\partial C_{wi}}{\partial t} = & \frac{\partial}{\partial z} \left[D_w(S^*) \frac{\partial C_{wi}}{\partial z} + v C_{wi} \right] \pm \frac{\partial C_{wi}}{\partial t} \Big|_{AC} + \frac{\partial C_{wi}}{\partial t} \Big|_{GD} \\ & + \frac{\partial C_{wi}}{\partial t} \Big|_{MA} + \frac{\partial C_{wi}}{\partial t} \Big|_B + \frac{\partial C_{wi}}{\partial t} \Big|_{NB} \end{aligned} \quad (5)$$

$$\frac{\partial C_{gi}}{\partial t} = \frac{\partial}{\partial z} \left[D_g(S^*) \frac{\partial C_{gi}}{\partial z} \right] \mp \frac{\partial C_{gi}}{\partial t} \Big|_{GD} \quad (6)$$

where $D_w(S^*)$ and $D_g(S^*)$ are the effective diffusion coefficients in the liquid and gaseous phases, while the rates of change in the terms on the right hand side of Eqs. (5) and (6) represent the net sink/source due to aqueous complexation (AC), gas dissolution and exsolution (GD), mineral adsorption and desorption (MA), biochemical reactions (B), and non-biochemical reactions (NB). Within our framework, all equilibrium reactions (i.e., AC, GD, and MA) and kinetic reactions (i.e., B and NB) occur in the liquid phase, except for the gaseous and aqueous exchangeable species in the terms labeled with GD in Eqs. (5) and (6).

Eq. (5) shows that transport of solute species occurs by molecular diffusion and by advection, the latter being proportional to Darcy's velocity v , which depends on gravitational advection (i.e., term in g in Eq. (1)). Eq. (6), instead, shows that diffusion in the gas phase is not affected by the gravitational acceleration.

2.3. Equilibrium reactions

To represent the geochemical system, a set of aqueous primary species is chosen that produces secondary species by aqueous complexation (AC), gas dissolution and exsolution (GD), and mineral adsorption and desorption (MA). These reactions, which occur at local equilibrium as introduced in Eq. (5), are fully determined by the equilibrium constants K_{AC} , K_{GD} , and K_{MA} , and do not depend explicitly on the gravitational acceleration. The relevant formulations for these reactions are detailed in Maggi et al. (2008), while Table 1 summarizes the primary species, the microbial functional groups (treated as primary species but not subject to reactions and transport), and the secondary species.

2.4. Kinetic reactions

Chemical and biological reactions are taken into account in TOUGHREACT by kinetic equations describing the change rate of an

Table 1

List of primary species and secondary species obtained by equilibrium reactions of primary species. The values of K_{AC} , K_{CD} , and K_{MA} were taken from the EQ3/6 database (Lawrence Livermore National Laboratory). AOB, NOB, DEN, and AER signifies, respectively, ammonia-oxidizing bacteria, nitrite-oxidizing bacteria, denitrifying bacteria, and aerobic heterotrophic bacteria.

Primary species		
Molecules	Ions	Microorganisms
H ₂ O	H ⁺	AOB
O ₂ (aq)	NH ₄ ⁺	NOB
NO(aq)	NO ₂ ⁻	DEN
N ₂ O(aq)	NO ₃ ⁻	AER
N ₂ (aq)	HCO ₃ ⁻	
CH ₂ O		
Secondary species		
Aqueous complexation		Log ₁₀ (K _{AC}) (T=20 °C)
OH ⁻ ↔ H ₂ O–H ⁺		13.99
NH ₃ ↔ NH ₄ ⁺ –H ⁺		9.24
HNO ₂ ↔ H ⁺ –NO ₂ ⁻		–3.22
HNO ₃ ↔ H ⁺ –NO ₃ ⁻		1.3
CO ₃ ²⁻ ↔ HCO ₃ ⁻ –H ⁺		10.32
CO ₂ (aq) ↔ HCO ₃ ⁻ +H ⁺ –H ₂ O		–6.34
Gas dissolution/exsolution		Log ₁₀ (K _{CD}) (T=20 °C)
CO ₂ (aq) ↔ HCO ₃ ⁻ +H ⁺ –H ₂ O		–7.81
NO(g) ↔ NO(aq)		–2.76
N ₂ O(g) ↔ N ₂ O(aq)		–1.60
N ₂ (g) ↔ N ₂ (aq)		–3.24
O ₂ (g) ↔ O ₂ (aq)		–2.89
NH ₃ (g) ↔ NH ₃ (aq)		11.04
Mineral adsorption/desorption		log ₁₀ (K _{MA}) (T=20 °C)
NH ₄ ⁺		3.08

Table 2

Biological and nonbiological reaction parameters for the nitrification and denitrification reactions. The values of the maximum specific rate constant μ , the half-saturation concentration for the electron donor K_C , electron acceptor K_e and inhibitor K_I , and mortality rates δ have been calibrated on the experimental data in Venterea and Rolston (2000). The values of biomass yield coefficients Y have been taken from Maggi et al. (2008).

Biological kinetic reactions	Mediator	μ (s ⁻¹)	K_C (mol L ⁻¹)	K_e (mol L ⁻¹)	K_I (mol L ⁻¹)	Y (mg mol ⁻¹)
NH ₄ ⁺ +3/2O ₂ (aq)→NO ₂ ⁻ +H ₂ O+2H ⁺	AOB	1.069 × 10 ⁻⁵	3.041 × 10 ⁻⁴	2.406 × 10 ⁻⁵	0	25 × 10 ⁻⁵
NO ₂ ⁻ +1/2O ₂ (aq)→NO ₃ ⁻ +H ₂ O+2H ⁺	NOB	1.798 × 10 ⁻⁵	2.984 × 10 ⁻⁴	2.406 × 10 ⁻⁵	0	20 × 10 ⁻⁵
2NO ₃ ⁻ +CH ₂ O→NO ₂ ⁻ +CO ₂ (aq)+H ₂ O	DEN	1.017 × 10 ⁻⁴	2.071 × 10 ⁻⁴	2.067 × 10 ⁻⁴	1.279 × 10 ⁻⁵	6.67 × 10 ⁻⁵
4NO ₂ ⁻ +CH ₂ O+4H ⁺ →4NO(aq)+CO ₂ (aq)+3H ₂ O	DEN	1.209 × 10 ⁻⁵	1.359 × 10 ⁻⁴	7.489 × 10 ⁻⁴	3.301 × 10 ⁻⁵	6.67 × 10 ⁻⁵
4NO ₂ ⁻ +CH ₂ O+4H ⁺ →4NO(aq)+CO ₂ (aq)+3H ₂ O	AOB	4.694 × 10 ⁻⁷	1.035 × 10 ⁻⁴	2.743 × 10 ⁻⁴	5.865 × 10 ⁻⁵	6.67 × 10 ⁻⁵
8NO(aq)+2CH ₂ O→4N ₂ O(aq)+2CO ₂ (aq)+2H ₂ O	DEN	1.001 × 10 ⁻⁴	6.241 × 10 ⁻⁵	1.755 × 10 ⁻⁴	5.519 × 10 ⁻⁵	6.67 × 10 ⁻⁵
8NO(aq)+2CH ₂ O→4N ₂ O(aq)+2CO ₂ (aq)+2H ₂ O	AOB	5.211 × 10 ⁻⁶	5.593 × 10 ⁻⁵	9.564 × 10 ⁻⁶	7.010 × 10 ⁻⁵	6.67 × 10 ⁻⁵
4N ₂ O(aq)+2CH ₂ O→4N ₂ (aq)+2CO ₂ (aq)+2H ₂ O	DEN	4.212 × 10 ⁻⁶	8.806 × 10 ⁻⁵	5.169 × 10 ⁻⁵	5.948 × 10 ⁻⁵	6.67 × 10 ⁻⁵
4N ₂ O(aq)+2CH ₂ O→4N ₂ (aq)+2CO ₂ (aq)+2H ₂ O	AOB	5.116 × 10 ⁻⁸	9.949 × 10 ⁻⁵	6.755 × 10 ⁻⁵	2.480 × 10 ⁻⁶	6.67 × 10 ⁻⁵
CH ₂ O+O ₂ (aq)→CO ₂ (aq)+2H ₂ O	DEN	1.569 × 10 ⁻⁶	10 × 10 ⁻⁵	1.129 × 10 ⁻⁴	0	6.67 × 10 ⁻⁵
CH ₂ O+O ₂ (aq)→CO ₂ (aq)+2H ₂ O	AER	6.341 × 10 ⁻⁶	10 × 10 ⁻⁵	2.406 × 10 ⁻⁵	0	6.67 × 10 ⁻⁵
Nonbiological kinetic reactions		μ				
3NO ₂ ⁻ +2H ⁺ →H ₂ O+NO ₃ ⁻ +2NO(aq)	–	2.206 × 10 ⁻⁹ (mol L ⁻¹ s ⁻¹)	–	–	–	–
CH ₂ O production ^a	–	2.440 × 10 ⁻⁴ (mg L ⁻¹ s ⁻¹)	–	–	–	–
HCO ₃ ⁻ production ^a	–	3.645 × 10 ⁻⁸ (mol L ⁻¹ s ⁻¹)	–	–	–	–
Mortality rate δ (s ⁻¹)						
	AOB	2.689 × 10 ⁻⁶	NOB	1.611 × 10 ⁻⁶	DEN	1.219 × 10 ⁻⁷
				AER	9.461 × 10 ⁻⁷	

^a CH₂O and HCO₃⁻ production follow a zero-order kinetics.

aqueous species concentration, C_{wi} , as due to production from substrates and consumption into products. In the general expression, production and consumption are proportional to the maximum specific reaction rate constant, μ , and by single or multiple Michaelis–Menten terms depending on the number of reactants. Each Michaelis–Menten term should include the half-saturation concentration of the electron donors, K_C , electron acceptors K_e , and of possible inhibitors, K_I .

Biological reactions are described in the same way as chemical reactions but, in this case, the reaction rate is also proportional to the biomass of the microbial functional groups that perform the reaction, to the biomass yield coefficient, Y , and to three environmental functions describing how the microorganisms respond to the soil water saturation, pH, and temperature (Maggi and Porporato, 2007). The biomass concentration of each functional group increases as the substrates are consumed and decreases by a first-order mortality rate δ (Monod, 1949). Gravity does not affect the chemical and biological parameters directly, but influences the microorganisms' metabolism via the soil moisture dynamics, nutrient advection, and pH as in Eqs. (1) and (5). The details of chemical and biological reactions are fully described in Maggi et al. (2008), while the kinetic reactions considered in this work are summarized in Table 2.

Table 3

Soil textural and hydraulic properties.

Soil parameters		Earth	Mars	Moon	ISS
g	(m s ⁻²)	9.806	3.69	1.622	0.001
ϕ	–	0.6	0.6	0.6	0.6
ρ	(kg m ⁻³)	2600	2600	2600	2600
k	(m ²) × 10 ⁻¹³	1.82 ^a	1.82	1.82	1.82
m	–	0.621 ^a	0.549	0.525	0.506
p_0	(Pa) × 10 ³	2.32 ^a	2.21	2.17	2.14
S_r	–	0.001	0.001	0.001	0.001
S_m	–	0.999	0.98	0.95	0.90

^a The values of k , m and p_0 relative to Earth were calibrated on the experimental data in Venterea and Rolston (2000). The value of m and p_0 relative to Mars, The Moon, and the orbiting station were obtained by interpolation of the experiments under terrestrial and microgravity in Heinse et al. (2007).

2.5. The modeled bioregenerative cropping unit

Several functioning schemes and technical designs have been proposed for space applications of cropping units (e.g., Hossner et al., 1991; Bingham et al., 2000; Jones and Or, 1998), including water and nutrient control systems (Hoehn et al., 2000; Morrow et al., 1994; Jones and Or, 1998; Bingham et al., 2002; Heinse et al., 2007), nutrient recycling (Volk and Rummel, 1987; Wheeler, 2003; Hanford, 2004), and decomposition of organic compounds (Finstein et al., 1999; Kanazawa et al., 2008), whereas less information is currently available on soil-based cropping units (Hoehn et al., 2000). Here, we have considered a bioregenerative unit as an isolated chamber that receives water and nutrient from a recirculation system, while the leachate is captured and sent back to a recycling unit. The recirculating unit, the recycling unit, and the plants to be cultivated are not directly investigated in this instance.

Modeling the cropping unit under various gravitational accelerations consisted of two phases. The first phase was aimed at determining the soil hydraulic and biogeochemical characteristics (i.e., texture, structure, porosity, permeability, organic matter content, and biochemical parameters) of a terrestrial agricultural soil under typical fertilization and irrigation practices. The second phase was aimed at applying these characteristics to the bioregenerative cropping unit under the gravitational acceleration of Earth (g), Mars (0.38 g), and the Moon (0.16 g), and the ISS (0 g), including the gravity corrections to the water retention curves and residual gas saturation (air pockets) of Eqs. (1)–(3). All units were exposed to the same temperature (20 °C constant over time), atmospheric total pressure, N_2 , CO_2 and O_2 partial pressures, boundary conditions, and nutrient and water application rates. However, the initial conditions were not necessarily the same in the four scenarios, and will be introduced in detail in the next sections.

3. Results

3.1. Experimental data and model calibration under terrestrial gravity

The physical and biochemical parameters used in TOUGHREACT 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, 2000). The soil of the tomato field was described in TOUGHREACT with a one-dimensional 60 cm long soil column with a spatial discretization of 1.25 cm for an experimental time of about 20 days starting in concomitance with the fertilizer application. Fertilization was modeled as an upscaled uniform concentration of 96 $g\ NH_3\ m^{-2}$ (0.12 $mol\ L^{-1}$ as NH_4^+) in the top 10 cm of the soil column as from field conditions. Irrigation was not recorded in the field but was calibrated against the experimental water saturation S , and resulted in one 24 h event at a rate of 8.64 $mm\ d^{-1}$ on day 9 followed by a second 96 h irrigation event at a rate of 34.6 $mm\ d^{-1}$ 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 $mm\ d^{-1}$. The irrigation and evaporation fluxes are the boundary conditions at the top of the column, while constant water saturation $S=0.5$ was imposed as the lower boundary condition (Table 4). Because fertilization and irrigation were applied before seedling developed, we have not included in TOUGHREACT water and nutrient uptake by plants, or any effects of roots on soil properties. The initial conditions are summarized in Table 5.

Calibration of the biogeochemical parameters describing the kinetic reactions (Table 2) and the soil hydraulic characteristics (Table 3) was carried out by minimizing the distance between experimental and modeled soil water saturation, S , pH, and concentration of NH_4^+ , NO_2^- and NO_3^- in the depth intervals 0–5 cm and 5–10 cm, and NO , N_2O and CO_2 fluxes. Calibration results are shown for 20 d observations in Fig. 2.

3.2. Experimental data and calibration of hydraulic parameters in microgravity

To model the bioregenerative unit under the gravitational acceleration of Earth, Mars, the Moon, and the orbiting space station, the effects of gravity on soil moisture dynamics and nutrient transport described in Section 2.2 and Section 2.3 were included using the entry values of g listed in Table 3. To account for changes in the soil water retention characteristic, corrections to the parameters m and p_0 were introduced on the basis of the observations in microgravity ($g \rightarrow 0\ m\ s^{-2}$) in three granular materials (Heinse et al., 2007). For each material, the values of m and p_0 were observed to decrease when the gravitational acceleration decreased from $g=9.806\ m\ s^{-2}$ to $g \rightarrow 0\ m\ s^{-2}$ (Fig. 3). The average rate of change

Table 4
Initial conditions of the soil-based bioregenerative cropping unit under the four scenarios of gravitational acceleration.

Depth (cm)	Earth ($g=9.806\ ms^{-2}$) ^a			Mars (0.38 g)			Moon (0.16 g)			ISS (0 g)		
	0–5	5–10	10–60	0–5	5–10	10–60	0–5	5–10	10–60	0–5	5–10	10–60
S	(0.9) 0.95	(0.95) 0.95	(0.95) 0.95	0.5	0.5	0.5	0.47	0.47	0.47	0.45	0.45	0.45
pH	6	7	7	6	7	7	6	7	7	6	7	7
$O_2(aq)$ ($10^{-4}\ mol\ L^{-1}$)	2.7	2.7	2.7	2.7	2.7	2.7	2.7	2.7	2.7	2.7	2.7	2.7
NH_4^+ ($mol\ L^{-1}$)	0.12	0.12	0	0.228	0.228	0	0.24	0.24	0	0.259	0.259	0
NO_3^- ($10^{-5}\ mol\ L^{-1}$)	1	1	1	1	1	1	1	1	1	1	1	1
NO_2^- ($10^{-5}\ mol\ L^{-1}$)	1	1	1	1	1	1	1	1	1	1	1	1
$NO(aq)$ ($mol\ L^{-1}$)	0	0	0	0	0	0	0	0	0	0	0	0
$N_2O(aq)$ ($mol\ L^{-1}$)	0	0	0	0	0	0	0	0	0	0	0	0
$N_2(aq)$ ($mol\ L^{-1}$)	0	0	0	0	0	0	0	0	0	0	0	0
HCO_3^- ($10^{-2}\ mol\ L^{-1}$)	6.236	8.852	0	6.236	8.85	0	6.236	8.85	0	6.23	8.85	0
CH_2O ($10^2\ mg\ L^{-1}$)	(3) 1.5	(3) 1.5	(3) 1.5	2.85	2.85	2.85	3.03	3.03	3.03	3.16	3.16	3.16
AOB ($mg\ L^{-1}$)	25.78	17.11	4.23	25.78	17.11	4.23	25.78	17.11	4.23	25.78	17.11	4.23
NOB ($mg\ L^{-1}$)	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5
DEN ($mg\ L^{-1}$)	6	6	7	6	6	7	6	6	7	6	6	7
AER ($mg\ L^{-1}$)	53	13	0.3	53	13	0.3	53	13	0.3	53	13	0.3

^a Values in parenthesis refer to the calibration on experimental field site while the other values refer to the simulations of the cropping unit on Earth for comparison with Mars, the Moon and the ISS.

Table 5
Boundary conditions of the soil-based bioregenerative cropping unit under the four scenarios of gravitational acceleration.

	Earth ($g=9.806 \text{ m s}^{-2}$)		Mars (0.38 g)	Moon (0.16 g)	ISS (0 g)
	Calibration	Simulation			
Top BC					
Evaporation (mm d^{-1})	2	1	1	1	1
Irrigation 1 (day 9) (mm d^{-1})	8.64	8.64	8.64	8.64	8.64
Irrigation 2 (day 10–14) (mm d^{-1})	34.6	34.6	34.6	34.6	34.6
Bottom BC					
Below 60 cm depth	$S=0.5$	$S=0.5$	$S=0.5$	$S=0.5$	$S=0.5$

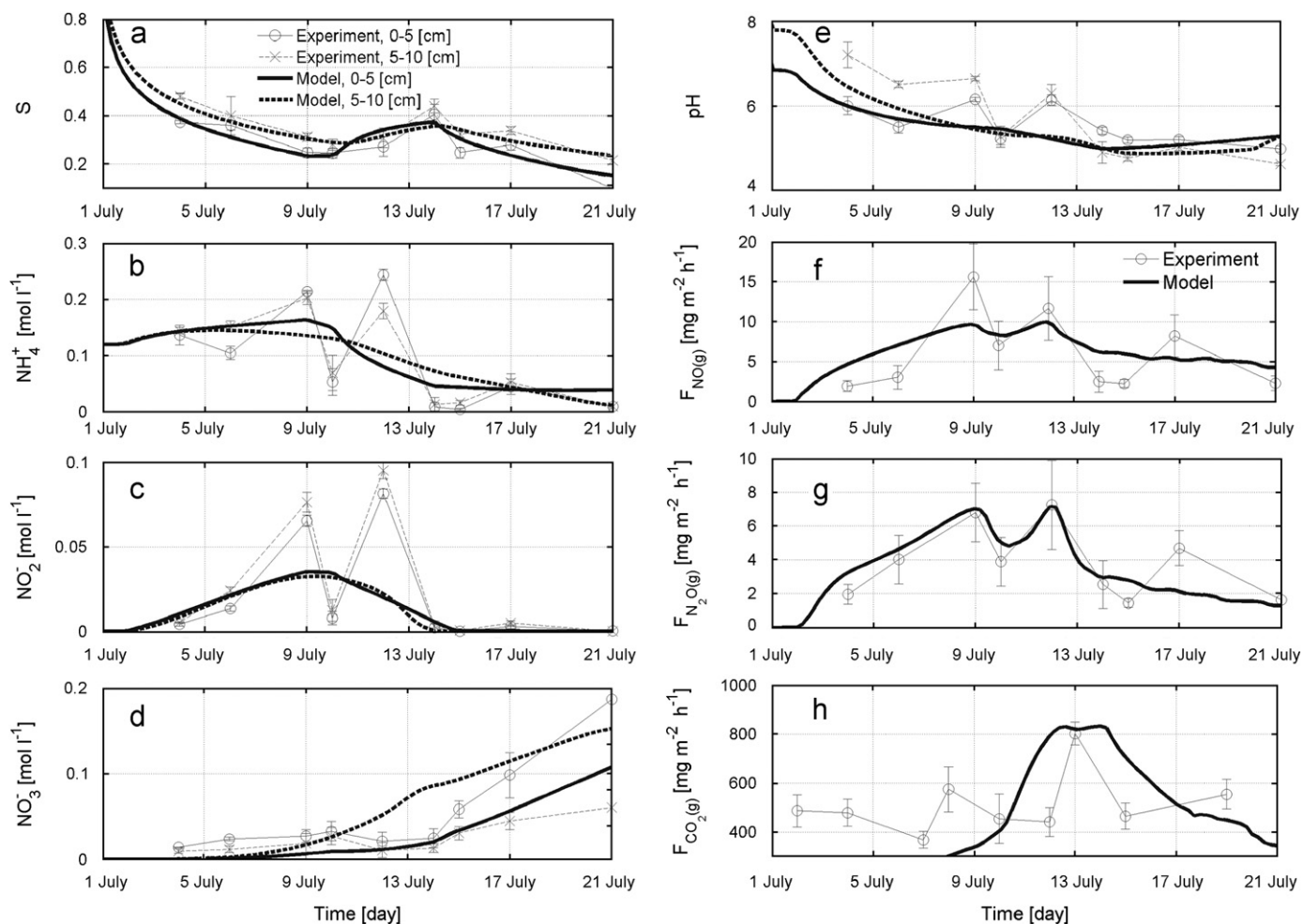


Fig. 2. (a)–(e) Experimental and modeled soil water saturation S , concentration of NH_4^+ , NO_2^- and NO_3^- , and pH at 0–5 cm depth and 5–10 cm depth over 20 day observation time. (f)–(h) Experimental and modeled fluxes of NO , N_2O , and CO_2 from the soil surface. Experimental data are redrawn from Venterea and Rolston (2000).

dm/dg and dp_0/dg have been calculated for the three materials, and have served to determining by linear interpolation the values of m and p_0 of the test crop unit on Mars, the Moon, and the ISS (Fig. 3, also reported in Table 3).

Because we have no experimental evidence of changes of S_m under changing gravitational acceleration, the effect of air-pocket formation was taken into account by arbitrarily reducing the maximum water saturation S_m from 0.99 on Earth to 0.9 in the orbiting station (Table 3). Overall, the effect of air pockets becomes relevant only at high saturation values while the soil systems investigated here will typically function at intermediate saturations, hence arbitrary values of S_m will not affect substantially our modeling results as long as they are suitably near 1.

Finally, although experimentally observed by Heinse et al. (2007), we have not included changes in porosity for decreasing gravitational acceleration.

3.3. Soil moisture dynamics under various gravities

The simulations of the bioregenerative unit were performed for the four gravitational scenarios retaining all initial conditions (i.e., solute and gaseous concentrations, microorganism concentrations, pH) and boundary conditions (i.e., fertilization and irrigation applications, and evaporation) identical. However, the initial soil water saturation, S , was set on Mars, the Moon, and the ISS to values lower

than on Earth so as to maintain depth- and time-averaged moisture contents at the same saturation in the four scenarios (i.e., $S=0.46$, Fig. 4a). This average saturation was chosen under the assumption to be optimal for plant development and microbial functioning over the

20-day simulation time, but also sets a criterion to detect relevant gravity-induced effects on the overall cropping unit.

In our simulation of a 20-day fertilization–irrigation cycle, about 65% of the water volume was lost from the soil on Earth by leaching (Fig. 4b). In contrast, only about 10% was lost from the Martian soil, 2% was lost from the lunar soil, and about 2% was gained within the soil in the orbiting station (Fig. 4b). The water holding capacity was very different in the four scenarios; the irrigation event applied from day 9 to day 13 did not result in water replenishment on Earth, while a replenishment of 5–10% was observed on Mars, the Moon, and the orbiting station (Fig. 4b).

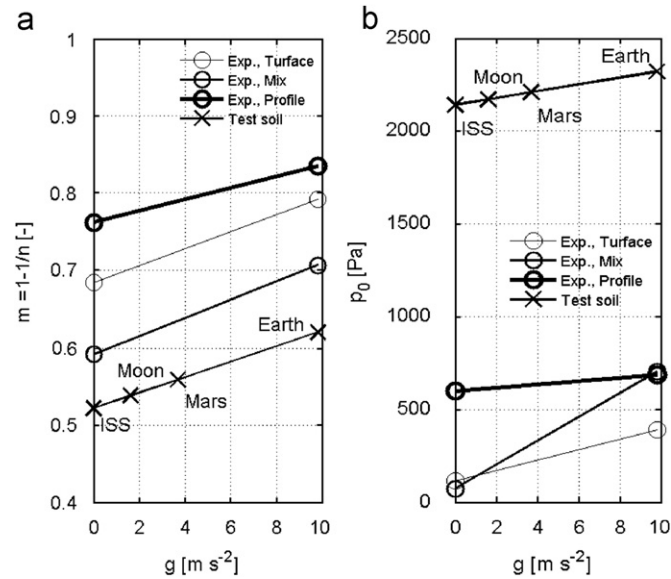


Fig. 3. Gravity-dependent van Genuchten parameters m and p_0 calibrated for three granular materials in 1 g and 0 g. The experimental average slope of m and p_0 is applied to the soil properties calibrated on Earth to derive m and p_0 on Mars (0.38 g), the Moon (0.16 g), and the ISS (0 g). Experimental data are redrawn from Heinsse et al. (2007).

3.4. Nutrient losses through leaching

The 20-day cumulative water and nutrient leaching from the cropping unit exposed to the Earth's gravity were taken as a reference to compare the leaching in the other scenarios. The gravitational acceleration on Mars, the Moon, and the ISS resulted in 90–100% lower water leaching than on Earth (Fig. 5). This low water leaching caused a 95–100% decrease in $\text{NH}_3(\text{aq})$, NH_4^+ , NO_2^- and NO_3^- solute leaching rates as compared to Earth (Fig. 5). These lower leaching rates were strictly due to the gravitational acceleration through Eq. (1), and to a smaller extent, to different van Genuchten parameters m and p_0 in Eq. (2) and Eq. (3), and to air pockets accounted for by S_m of Eq. (4).

3.5. Nutrient inventory and cycling

An analysis of the soil N inventory in the four gravity scenarios showed that the terrestrial gravity resulted in a rapid N depletion

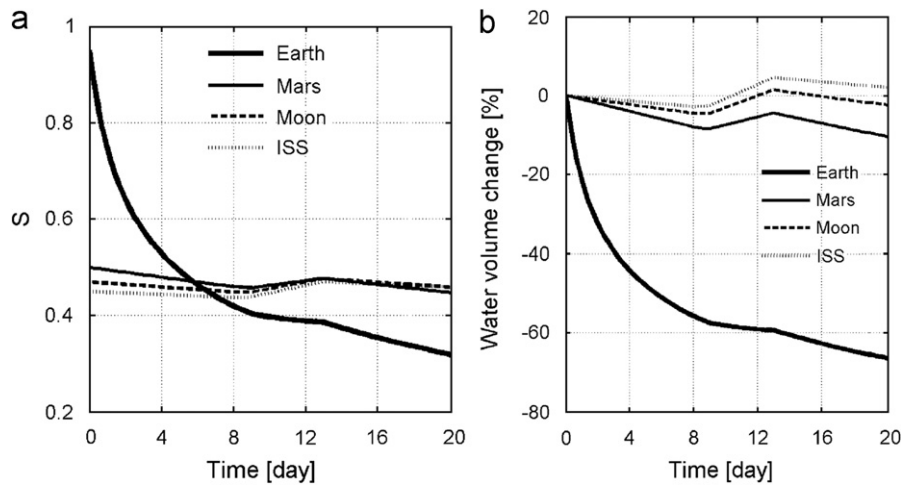


Fig. 4. (a) Depth-averaged soil moisture content over time calculated over 60 cm soil profile. (b) Net water volume change percent over time with respect to initial water volume. Results refer to Earth, Mars, the Moon, and the international space station (ISS).

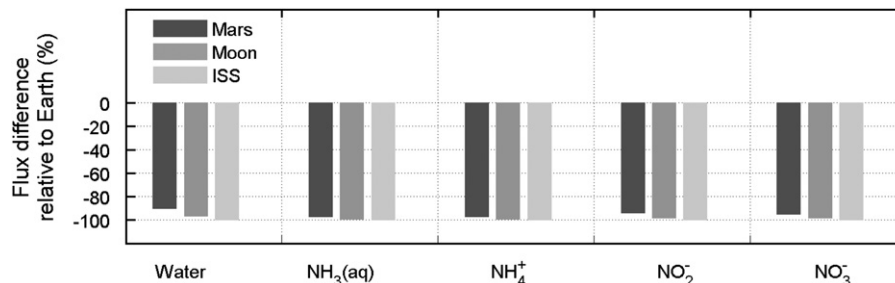


Fig. 5. Difference in cumulative leaching of water, NH_3 , NH_4^+ , NO_2^- , and NO_3^- solutes at 60 cm depth from soil systems subject to the gravity of Mars (0.38 g), the Moon (0.162 g) and in the orbiting station (0 g) relative to Earth ($g=9.806 \text{ m s}^{-2}$). The cumulative fluxes are calculated over a 20-day period. The differences relative to fluxes observed on Earth are expressed in percent (%).

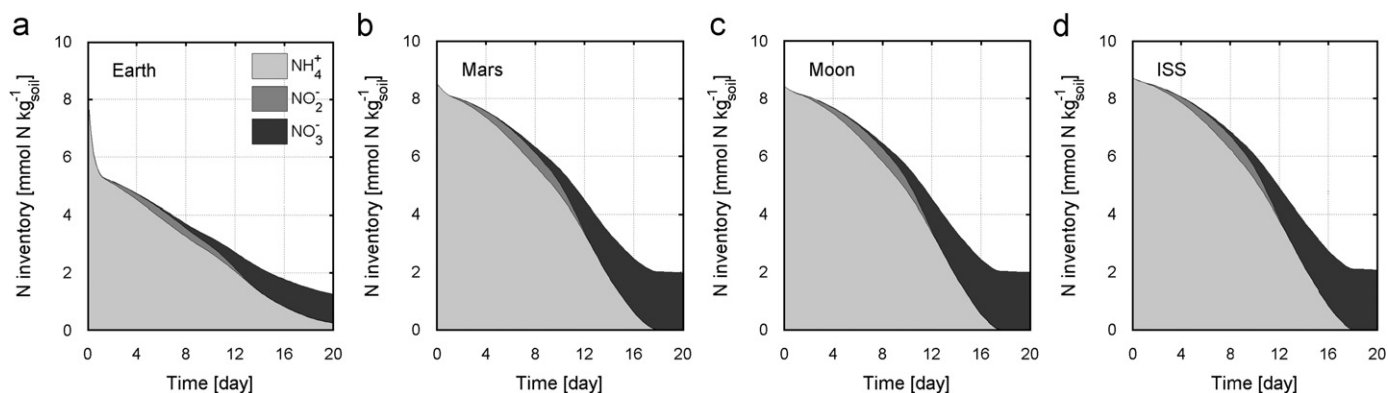


Fig. 6. Depth-averaged inventory of solute N ions over time in the cropping units subject to the gravity of Earth (a) $g=9.806 \text{ m s}^{-2}$, Mars (b) 0.38 g , the Moon (c), 0.162 g and in the orbiting station (d) 0 g .

(Fig. 6a) with about 30% of the N lost during the first day of the experiment, which was substantially correlated to the rapid loss of water depicted in Fig. 4b. Afterwards, the total N load on Earth decreased with a slower, nearly constant rate (Fig. 6a). Conversely, soil N depletion on Mars, the Moon, and the ISS occurred with a variable rate, but without any abrupt loss in the first day as observed on Earth (Fig. 6b–d).

In the four scenarios investigated here, NH_4^+ , which was initially supplied as N-fertilizers, was subject to a substantial decrease (i.e., by leaching and nitrification) (Fig. 6). NO_2^- and NO_3^- anions were sequentially produced through nitrification after 4 and 9 days, respectively, and showed a relatively similar trend in the four scenarios: NO_2^- was consumed to extinction within the first 12 days, while NO_3^- slightly accumulated in the soil as the gravitational acceleration decreased from $g=9.806 \text{ m s}^{-2}$ (Earth) to 0 g (ISS) due to lower leaching rate.

It should be noted that leaching in micro- and hypogravity accounted for only a small fraction of water and N losses as compared to Earth ($<10\%$, Fig. 5) but did not result in a substantial increase in solute residence time within the root zone; in fact, the concentrations of NH_4^+ , NO_2^- and NO_3^- on Mars, the Moon, and the ISS were higher than on Earth for about 12 days but ended with similar values ($1.5\text{--}2 \text{ mmol N kg}_{\text{soil}}^{-1}$) in all scenarios at the end of the fertilization–irrigation cycle (day 20, Fig. 6). This pattern suggests that the turnover time of N solute ions was nearly the same in all scenarios and that lower N leaching rate was counterbalanced on Mars, the Moon and the ISS by a higher consumption of NH_4^+ and NO_2^- through nitrification, and of NO_3^- through denitrification.

A different pattern was found for the concentration of dissolved organic carbon (DOC); we observed that the cropping unit on Earth showed DOC depletion mainly caused by leaching (Fig. 7), while on Mars, the Moon, and the ISS DOC concentration increased over time. This was caused by the interplay between leaching rate (smaller than on Earth in these scenarios), DOC production (modeled as a zero-order kinetics, Table 2), and DOC microbial consumption. Because of these interactions, and the lower gravitational acceleration, DOC production was dominant during the first 10 days as compared to Earth, while microbial consumption during aerobic respiration and denitrification likely caused the deflection in DOC concentration after day 10 (Fig. 7).

3.6. Nutrient losses through gas emissions

An analysis of the cumulative gas emissions from the surface of the cropping units on Mars, the Moon, and the ISS relative to the emissions on Earth showed that hypogravity has an important

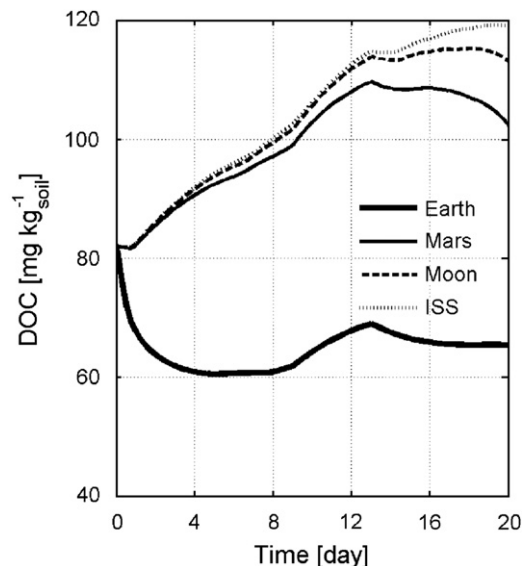


Fig. 7. DOC depth-averaged concentration on Earth, Mars, the Moon and the international space station (ISS).

impact (Fig. 8). NH_3 and NO gas emissions were 80–90% and 25–35% lower than on Earth (decreasing proportionally with the gravitational acceleration throughout each scenario) while N_2O , N_2 and CO_2 gas emissions were about 80%, 190–220% and about 40% higher, respectively, compared to on Earth (Fig. 8).

The relatively important emission of N_2O and N_2 gases from the soil system on Mars, the Moon, and the orbiting station suggests therefore that nitrification and denitrification occurred at higher rates than on Earth and explain why a lower leaching rate did not result in the accumulation of N solute species within the root zone as compared to Earth (see N inventories in Fig. 6). The higher rate of denitrification explains also higher CO_2 production and emission in low-gravity scenarios (Fig. 8), where N reduction performed by the DEN microbial functional group occurs at the expenses of oxidation of DOC (i.e., the donor) and produces CO_2 gas through respiration.

3.7. Microbial biomass inventory and stratification

The features evidenced in the previous sections suggest a different nutrient loss pathway in the cropping units on Mars, the Moon, and the ISS compared to on Earth. The large production of N gases and the relatively higher CO_2 emissions indicate that the

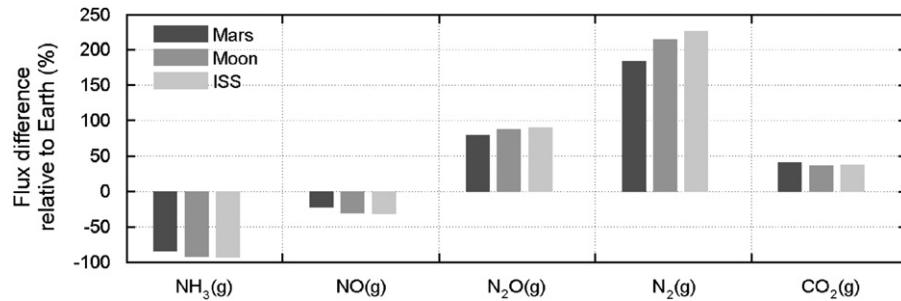


Fig. 8. Difference of cumulative NH₃, NO, N₂O, N₂, and CO₂ gas emissions from the surface of soil systems subject to the gravity of Mars (0.38 g), the Moon (0.162 g) and in the orbiting station (0 g) relative to Earth ($g=9.806 \text{ m s}^{-2}$). The cumulative fluxes are calculated over a 20-day period. The differences relative to fluxes observed on Earth are expressed in percent (%).

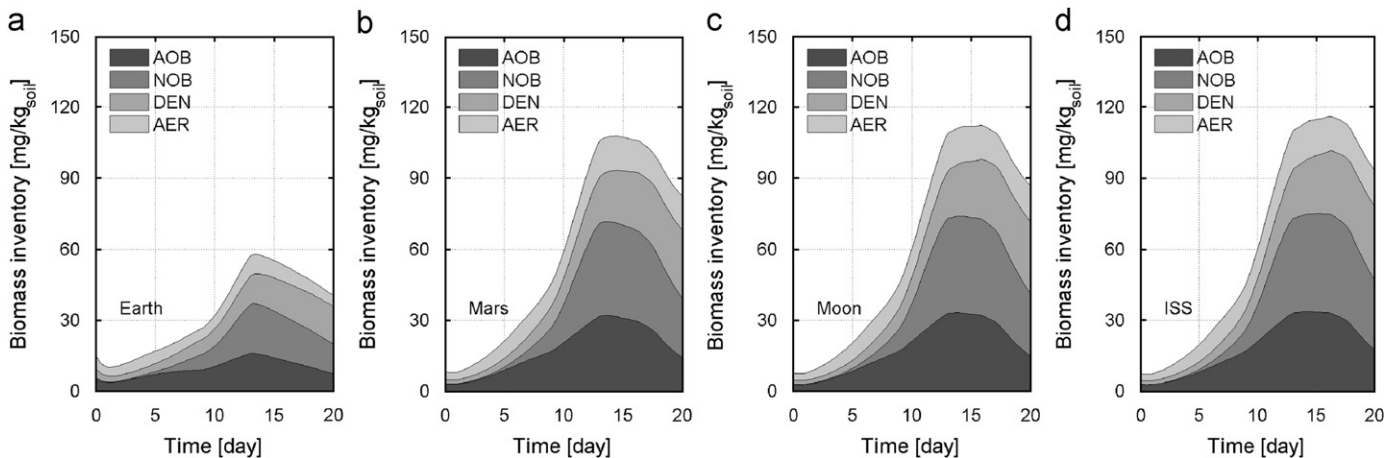


Fig. 9. Depth-averaged biomass inventory of ammonia-oxidizing bacteria (AOB), nitrite-oxidizing bacteria (NOB), denitrifying bacteria (DEN), and aerobic bacteria (AER) functional groups on (a) Earth (blue), (b) Mars (red), (c) the Moon (gray) and (d) the orbiting station (green).

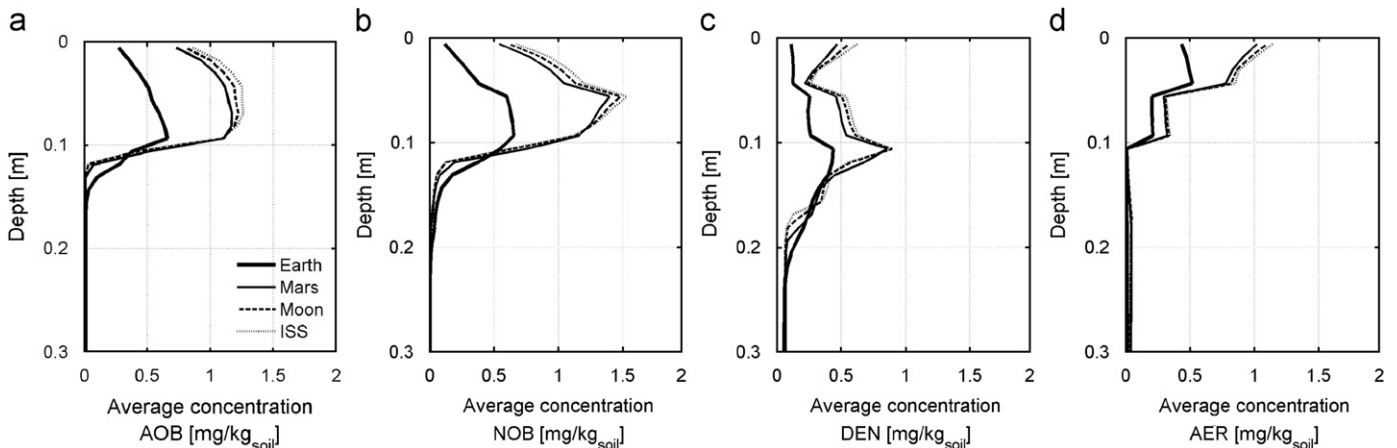


Fig. 10. Time-averaged biomass concentration of (a) ammonia-oxidizing bacteria (AOB), (b) nitrite-oxidizing bacteria (NOB), (c) denitrifying bacteria (DEN), and (d) aerobic bacteria (AER) functional groups on Earth, Mars, the Moon and the international space station (ISS).

biological activity in scenarios of low gravitational acceleration was higher than in the terrestrial cropping unit. The microbial inventory in the four scenarios shows that the density of each microbial functional group was progressively increasing with decreasing gravity (Fig. 9). As mentioned earlier, these higher microbial densities principally occurred because of a lower nutrient leaching on Mars, the Moon, and the ISS (Fig. 2). In these low-gravity scenarios, a lower leaching rate exposed the microorganisms to NH₄⁺ for a longer time, thereby feeding the

chain reactions that led to higher production of NO₂⁻ through nitrification by ammonia-oxidizing bacteria (AOB), of NO₃⁻ through nitrification by nitrite-oxidizing bacteria (NOB), and of reduced N gases when NO₃⁻ remained available to denitrifying bacteria (DEN). In these chain reactions, all microbial functional groups became exposed to higher substrate concentrations and grew faster than on Earth, but the increased N gas emissions in scenarios of lower gravity can ultimately be ascribed to a higher AOB and NOB concentration since these microbial functional groups were

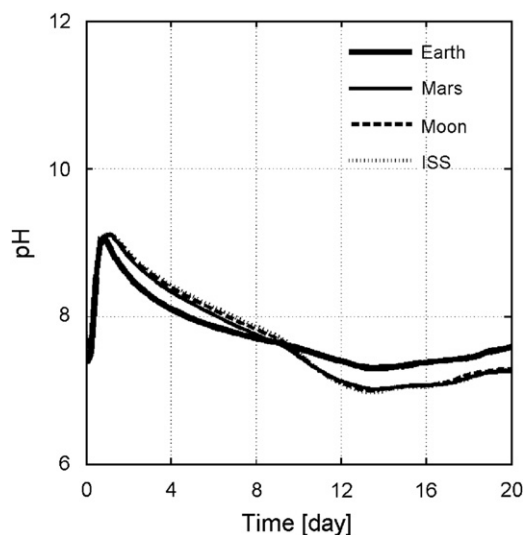


Fig. 11. Depth-averaged pH over time.

responsible for producing NO_3^- ion next consumed by DEN through the sequence of reactions $\text{NO}_3^- \rightarrow \text{NO}_2^- \rightarrow \text{NO} \rightarrow \text{N}_2\text{O} \rightarrow \text{N}_2$.

An analysis of the vertical stratification of the various microbial functional groups showed that gravitational accelerations lower than the Earth's did not substantially alter the microbial spatial organization even under conditions for which nutrients were delivered by diffusion rather than advection processes (Fig. 10). The functional groups that require oxygen (AOB, NOB, and AER) predominantly occupied the top 10 cm of the soil (Fig. 10a, b and d), whereas the anaerobic DEN functional group was mainly located at deeper depth (Fig. 10c). Overall, N-oxidizing bacterial groups (AOB and NOB) experienced a growth phase that led to 60–110% higher biomass as a consequence of lower NH_4^+ leaching rate as the gravity decreased throughout the four scenarios. This result corroborates our explanation for a total N load similar in all scenarios of gravitational acceleration at day 20 (Fig. 6), which resulted in substantially higher rates of N_2O and N_2 gas emissions in low-gravity scenarios (Fig. 8).

3.8. pH

The time evolution of the depth-averaged pH was very similar in the four scenarios over the 20 day fertilization–irrigation cycle analysed here (Fig. 11). The soil systems, therefore, did not show unstable dynamics even if the concentration of AOB and NOB functional groups (which are responsible for soil acidification) was increasing throughout scenarios of decreasing gravitational acceleration.

4. Discussion

The results presented here highlight important aspects for soil-based agriculture. The hypogravity hydraulics and biogeochemistry do not seem to jeopardize the functioning of a soil-based bioregenerative cropping unit for space applications over short time scales (few weeks). Rather, the soil systems tested here seem to offer an opportunity to practice agriculture in hypogravity environments with lower water and nutrient footprint than on Earth due to reduced leaching rates. We estimated that the water volume needed for irrigation could be between 40% and 70% lower than on Earth for the scenarios analysed here. Space agriculture practiced in hypogravity would also require lower mineral N supply due to lower leaching loss rate; in fact, a 30–50% reduction of N supplied from fertilizers would not limit N delivery to soil

microorganisms but would result in an important reduction in N losses as gaseous emissions. These aspects suggest a scenario in which the modern techniques of precision fertilization and irrigation could be further optimized for reduced gravity as in the earlier water and nutrient delivery systems investigated for space applications (e.g., Morrow et al., 1994; Bingham et al., 2002).

A bioregenerative cropping unit that uses Earth-like soil media could carry beneficial effects in extraterrestrial outposts and orbiting stations; in fact, the variety of microbial communities present in soils can metabolize most compounds of potential toxicity and mineralize organic matter whereas these capabilities are not present in hydroponic, aeroponic, zeoponic, and membrane systems (Nelson et al., 2008). This aspect is particularly important in relation to the removal of debris and root exudates by biodecomposition, which could otherwise cause clogging in artificial porous media, where microorganism concentration and diversity are expected to be lower (i.e., zeoponics) or not present (hydroponics and aeroponics). The type of soil for use in cropping units in space, however, should be chosen to allow for a reliable water and nutrient control. While the soil used here was made of relatively fine grains, coarser granular materials (i.e., with higher values of m and lower capillary pressure p_0 than tested here, Fig. 3) could meet more closely the water retention characteristics in Heinse et al. (2007).

The comparative analyses presented here were limited to one cycle of fertilization and irrigation that lasted for 20 days before plant development. Within the purpose of designing a long-term life support system for space exploration, the long-term soil ecodynamics response under hypogravity should also be assessed. In this instance, two aspects should be taken into account explicitly. The first is the effect of plants dynamics on nutrient and water uptake and CO_2 root respiration, not included in this work. Plant water demand in microgravity is not fully understood yet. In the experiments in the LADA cropping unit, plant water demand in microgravity appeared comparable to the one on Earth (Bingham et al., 2002), whereas direct measurements of transpiration in microgravity showed a decreased demand as a result of reduced convection around leaves (Hirai and Kitaya, 2009). The second aspect is the recycling of organic matter and its use as a source of nutrient in place of externally-produced fertilizers. This aspect has been considered in separate instances for composting (Kanazawa et al., 2008; Volk and Rummel, 1987; Finstein et al., 1999) and assessing the carbon budget and turnover (Wheeler, 2003), but should be implemented within a wider framework of life cycle analysis to properly assess the long-term C and N features of a life support system based on soils.

Although we focused this work mainly on N-based nutrients and DOC, it is important that future work addresses the biogeochemical cycling of other macronutrients essential for plants such as phosphorus (P), sulphur (S), potassium (K), magnesium (Mg), and calcium (Ca), and essential micronutrients 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 terrestrial soils could adapt to and be affected by hypogravity. Salisbury (1992) has expressed concern about possible catastrophic failures of a bioregenerative cropping unit from diseases of plants, humans or animals. Epidemiological aspects in microgravity cropping units for space applications have not been investigated yet, and will require careful consideration.

5. Conclusions

This comparative study of soil hydraulics, biogeochemical processes, and microbial biomass dynamics under various scenarios of

gravitational acceleration indicates that soil-based bioregenerative systems could function under micro- and hypogravity in a similar way as in the terrestrial gravity. For gravitational accelerations decreasing from $g=9.806\text{ m s}^{-2}$ (Earth) to 0.38 g (Mars), 0.16 g (Moon) and nearly 0 g (ISS) we have observed important decreases in water and solute nutrient leaching, and increasing emissions of N gases and CO_2 . Under these gravitational accelerations, nutrient availability to microorganisms was higher and resulted in a microbial biomass concentration 60–100% higher than on Earth, while their depth stratification was practically unchanged.

These results provide evidence that soil-based agriculture in micro- and hypogravity would require relatively small amounts of water and nutrients supplied from external sources (i.e., fertilizers) as compared to Earth, and corroborate the idea that precision water and nutrient dosing systems can be used to satisfy plant demand also in soils. The advantage of bioregenerative soil-based systems *versus* other constructed media is the potential to compost organic residuals from roots that could otherwise clog other microorganism-free growing media, compost organic wastes (e.g., non edible plant mass), and filter water and other liquids while reducing consumable on-board resources, energy, and maintenance operations as compared to other systems (aeroponics, hydroponics and zeponics). Ideally, these features represent an attractive option to support life for relatively extended time periods such as required for an expedition to Mars, or for a permanently manned outpost on the Moon. However, many aspects still remain unknown, including the coupled soil-plant dynamics, and the long-term resilience of a bioregenerative cropping unit. Corollary aspects include the potential use of *in-situ* derived soil resources, and the long-term management of soil nutrients and gases within the unit.

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