Control of habitat's carbon dioxide level by biomass burning

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Abstract

Consider a free-space settlement with a closed ecosystem. Controlling the habitat's carbon dioxide level is a nontrivial problem because the atmospheric carbon buffer per biosphere area is smaller than on Earth. Here we show that the problem can be solved by burning agricultural waste. Waste biomass is stored and dried, and burned whenever plant growth has lowered the atmospheric carbon dioxide level so that replenishment is needed. The method is robust, low-tech and scalable. The method also leaves the partial pressure of oxygen unchanged. In the initial growth phase of the biosphere, one can obtain the carbon dioxide by burning sugar or carbon, which can be sourced from carbonaceous asteroid materials. This makes it possible to bootstrap the biosphere without massive biomass imports from Earth.

Keywords: space settlement, closed ecosystem, carbon cycle

1. Introduction

Space settlements need a nearly closed ecosystem for food production. One of the fundamental parts of a closed ecosystem is the carbon cycle. In the carbon cycle (Fig. 1), plants fix carbon from atmospheric CO_2 by photosynthesis, producing biomass [approximately sugar, net formula $n(CH_2O)$] and liberating oxygen,

$$CO_2 + H_2O + \text{light} \rightarrow CH_2O + O_2. \quad (1)$$

The biomass is consumed and metabolised by decomposers, animals and people. Metabolism is the reverse reaction of photosynthesis,

$$CH_2O + O_2 \rightarrow CO_2 + H_2O + \text{energy}. \quad (2)$$

On Earth, the atmospheric CO_2 and the biospheric CH_2O contain comparable amounts of carbon. This is so because the amount of carbon in the atmospheric CO_2 is 1.66 kgC/m^2, while the world average biospheric carbon is 1.08 kgC/m^2 [1][1]. Because the atmospheric carbon buffer is large, on Earth the atmospheric CO_2 level is not sensitive to fluctuations in the primary production of the biosphere. The Earth's atmosphere is massive (10 tonnes per square metre), while most of Earth's surface area is open ocean, desert or glacier so that the globally averaged biomass areal density is only moderate. For example in average African tropical rainforest, the carbon stock is 18.3 kgC/m^2 i.e. 183 Mg/ha [2, Table 2], which is as much as 17 times larger than the global average.

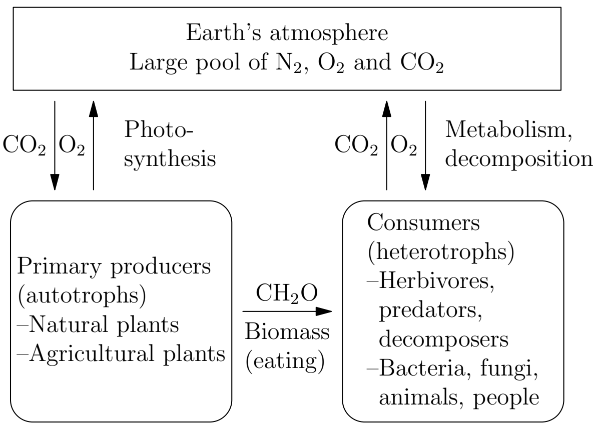

Figure 1: Carbon cycle on Earth.

In a space settlement, the atmosphere mass is likely to be much less than 10 tonnes/m^2. In O'Neill's original large habitat concepts [3, 4], the atmosphere had several kilometres depth. However, a massive atmosphere includes a lot of nitrogen. Nitrogen is not too abundant on asteroids, and would only be widely available in the outer solar system. One way to avoid the nitro-

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[1] 550 billion tonnes of carbon[1, Table 1] is 1.08 kgC/m^2.

gen supply problem would be to use a reduced pressure pure oxygen atmosphere, but then the risk of fire would be increased since the flame is not cooled by inert gas. Also birds and insects (needed for pollination) would have difficulty in flying in a pure oxygen atmosphere, because its mass density would be several times less than on Earth. Hence it is likely that most settlements would prefer to use a shallower N_2/O_2 atmosphere of e.g. $\sim$ 50 m depth [5]. A 50 m height allows forests with maximum tree height of $\sim$ 30 m plus some room for horizontal winds to mix gases above the treetops. The nitrogen (47 kg/m^2) can be obtained from the asteroids, as a byproduct of the mining that produces the combined structures and radiation shielding of the settlement (10^4 kg/m^2).

Carbon dioxide is necessary for plants to grow. To maintain good growth, the concentration should be at least $\sim$ 300 ppmv (parts per million by volume). The pre-industrial level on Earth was 280 ppmv, which, as we know, already allowed plants to grow reasonably well. On the other hand, for human safety the amount should not exceed $\sim$ 2000 ppmv. The U.S. occupational safety limit for a full working day is 5000 ppmv. The atmospheric concentration must be clearly less, however, since local concentration near sources is always higher than the atmospheric one. An example of local source is indoors where people continuously produce CO_2 by breathing.

A shallow atmosphere is unable to absorb fluctuations in the biomass carbon pool while keeping the CO_2 level within safe bounds. The timescales can be rather fast. A tropical rainforest can bind 2.0 kgC/m^2/year [6, 7], so in a shallow 50 m atmosphere, maximal plant growth could reduce the concentration of CO_2 by 1000 ppmv in as short time as 4.5 days. In temperate forest the rate of biomass production is somewhat less (1.25 kgC/m^2/year) and in cultivated areas even less (0.65 kgC/m^2/year)[6, 7], but the timescales are still only weeks. Hence the atmospheric CO_2 must be controlled by technical means, which is the topic of this paper.

2. Feasibility of a closed ecosystem

There are many examples of nearly semi-closed small ecosystems that interact with the rest of Earth's biosphere mainly via air only: a potted flower, a vivarium, a fenced garden, a small island, etc. To turn a semi-closed system into a fully closed one, one only needs to worry about a few gases. This is an engineering task, where the complexity of biology has been factored out. More specifically, there are five parameters to consider:

1. O_2 partial pressure. Oxygen is needed for humans and animals to breath, and the partial pressure should be about 0.21 bar.
2. N_2 partial pressure. Nitrogen is needed for fire safety and for birds and insects to fly, and the partial pressure should be about 0.79 bar.[2]
3. CO_2 concentration. Carbon dioxide is needed by plants to grow, but too high a value is unsafe to people. The allowed range is 300–2000 ppmv.
4. CH_4 concentration. Methane is not needed so the lower limit is zero, but if generated by the biosphere, it is tolerable up to 30 mbar, which is well below the ignition limit of 44 mbar. Methane's only health effect is oxygen displacement, which is however negligible at 0.03 bar.
5. Other gases should remain at low concentration.

Considering oxygen, a biosphere does not fix it from the atmosphere. The oxygen atoms that biomass CH_2O contains originate from the water that enters photosynthesis. When organisms do metabolism and breathe (Eq. 2), they transform O_2 molecules into CO_2 molecules, but the process involves no net transfer of O atoms from the atmosphere into the body. Hence one does not need to do anything special to maintain the right O_2 partial pressure.

Considering N_2, a biosphere fixes some of it since nitrogen is a key nutrient, present in proteins and DNA. The C:N ratio of cropland soil is 13.2 and for other biomes it varies between 10.1 and 30 [8, Table 1]. For leaves, wood and roots the C:N ratio is higher [8]. To get an upper limit, the carbon stock of average African rainforest is 18.3 kgC/m^2 [2]. With the minimal soil C:N ratio across biomes of 10.1, this corresponds to 1.81 kgN/m^2 of fixed nitrogen. But the mass of nitrogen in a 50 m high atmosphere is 46 kgN/m^2, so clearly the biosphere can assimilate only a small fraction of atmospheric N_2. Hence one does not need to do anything special with N_2, either. Its partial pressure will remain sufficiently close to the initial value. Circulation of nitrogen from the point of view of nutrient supply is a related topic [9], which is however outside the scope of this paper.

Thus, since N_2 and O_2 are not changed too much by the biosphere, the task of maintaining a good atmosphere is reduced to three issues:

1. Maintaining CO_2 within the 300–2000 ppmv bounds. This is treated in the next section.

[2] We do not consider argon and other noble gases because they are even less abundant on asteroids than N_2. Also, at high concentrations some noble gases have narcotic effects.

2. Ensuring that if net methane is emitted by the biosphere, its concentration does not increase beyond $\sim 3\,\%$ by volume. [3]
3. Ensuring that the concentration of other gases stay low. This may possibly happen automatically, because plants are known to remove impurities from air [10]. We shall say a bit more on this in the Discussion section below.

3. Biomass burning

Above we described the carbon cycle problem of the orbital space settlement. The problem is that the settlement's atmosphere is much shallower than on Earth, and hence the atmospheric carbon buffer is much smaller than the biospheric carbon stock. Fluctuations in the amount of biospheric carbon can occur for many reasons, and the fluctuations would cause the atmospheric CO_2 concentration to go off bounds.

A way to solve the problem is to store some biomass and to burn it when the atmosphere needs more CO_2 (Fig. 2). Agricultural waste is a necessary byproduct of food production. One stores the waste biomass in such a way that it does not decompose and then burns it at a controlled rate. Methods to store biomass include drying, freezing and freeze-drying. Drying is feasible at least if the relative humidity is not too high.

It is sufficient for only part of the biomass to go through the storing and burning pathway. The higher the burned fraction is, the larger is the CO_2 control authority of the scheme. The control authority is sufficient if the total amount of carbon in the settlement exceeds the maximum mass of carbon that can be fixed in living organisms at any one time. When the atmospheric CO_2 drops below a target value, one burns some stored biomass. If there is too much of CO_2 in the atmosphere, one ceases the burning activity for a while. After some delay plant growth will take down the CO_2 concentration.

Burning consumes oxygen, but the same amount of oxygen is liberated into the atmosphere when the CO_2 is used by photosynthesis (Eqs. 1 and 2). Thus the O_2 concentration stays constant, apart from an insignificant part that exists temporarily as CO_2. This is especially advantageous in the build-up phase of the biosphere. In the build-up phase, one needs to add carbon constantly to the atmosphere, as trees and other plants are growing. Depending on the type of ecosystem we are building, the growth phase might last up to tens or even hundreds of years as trees grow and the soil builds up. It is not necessary to wait for the growth phase to finish until people can move in, but while the growth phase is ongoing, one must be prepared to put in new carbon as needed to avoid CO_2 starvation. If this carbon would be added in the form of new CO_2 from an external tank, for example, the level of atmospheric oxygen would build up. However, if one adds the carbon by burning biomass, sugar or carbon, the O_2 level stays constant.[4] Carbon can be sourced from carbonaceous asteroids. Possibly sugar [net formula $n(CH_2O)$] can be synthesised from C-type asteroids as well. Thus the biosphere can be bootstrapped without massive importing of biomass from Earth.

When burning biomass, the rate must be controllable and fire safety must be maintained. One also wants to minimize smoke production (particulate emission), because otherwise the settlement's sunlight-passing windows would need frequent washing and because we want to avoid atmospheric pollution [11]. One way to facilitate clean burning is to mechanically process the biomass (or part of it which is used in the ignition phase) into some standardised form such as pellets [12] or wood chips. It is also possible to use a bioreactor to turn the biomass into biogas (methane) which burns without smoke. To further reduce smoke, one might add an electrostatic smoke precipitator in the smokestack. A combination of approaches is also possible. One can ignite the flame using easy fuel and then continue with more unprocessed material. The burning activity could be continuous, but in a 50 m high atmosphere, enough constant CO_2 is reached by a daily burning session.

Atmospheric pollution should be avoided, so smoke production should be minimised. However, plants and soil are known to clean up the atmosphere rather well [10]. Hopefully, if the above measures to promote clean burning are used, the plants can accomplish the rest so that the atmosphere remains clean. To investigate the question experimentally, one could burn biomass inside a greenhouse by different methods, while using standard air quality monitoring equipment for measuring the atmosphere.

[3] On Earth the methane concentration is 1.8 ppmv, which is responsible for part of the terrestrial greenhouse effect. For atmospheric height of 50 m, a similar greenhouse effect arises at 200 times higher concentration, i.e. at 360 ppmv. Thus a 3 % (30,000 ppmv) methane concentration would cause a significant greenhouse effect for a 50 m atmosphere, which should be taken into account in the settlement's heat budget. Greenhouse effects are nonlinear so quantitative prediction would need modelling.

[4] Burning hydrocarbons ($\sim CH_2$) in the buildup phase is not recommended, because then net consumption of O_2 would take place as oxygen would be bound with hydrogen to make water.

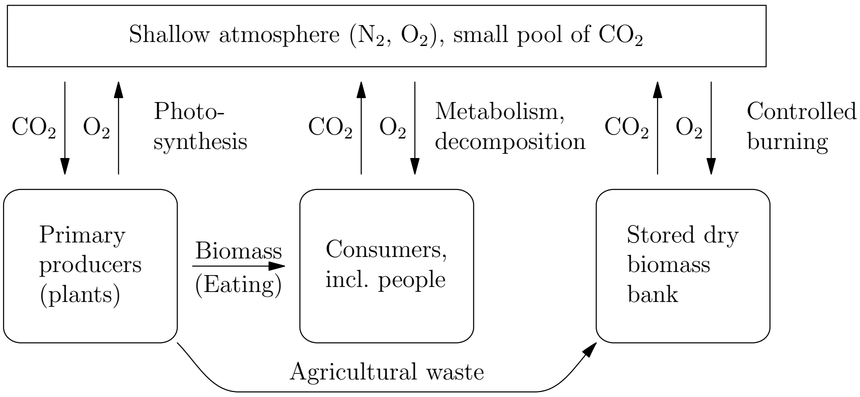

Figure 2: Carbon cycle in the settlement.

In a rainforest, the maximum carbon fixation rate is 2 kgC/m^2/year and in a cultivated area it is 0.65 kgC/m^2/year (see last paragraph of Introduction). If the average is $\sim$ 1 kgC/m^2/year and if 50 % of it is burned while the remaining part is decomposed naturally or eaten as crop, then the burned amount is 0.5 kgC/m^2/year, which corresponds to 34 kg of dry biomass per hectare per day. When wood is burned, the mass fraction of ash varies between 0.43 and 1.8 per cent [13, Table 1], so that the ash produced is a few hundred grams per day per hectare. The ash must be distributed evenly back into the environment. The amount of ash is modest enough that the settlers could even do the spreading manually if they wish. The heat produced by the burning is of the order of 0.8 W/m^2 as a temporal average, which is two orders of magnitude less than the heat dissipation of sunlight, or artificial light if that is employed.

In reality, a smaller burning rate than this calculation would probably suffice. It is only necessary to burn enough biomass to maintain sufficient control authority of the CO_2 level. Burning as much 50 % of the growth is likely to be overkill, but we assume it to arrive at a conservative estimate.

Animal and human wastes are not burned, but composted to make leaf mold which is spread onto the fields. Our recommendation is to primarily burn agricultural plant waste which is poor in non-CHO elements, comprising substances such as cellulose, lignin and starch. In this way we avoid unnecessarily releasing fixed nitrogen and other valuable nutrients into the atmosphere, where they would also be pollutants.

4. Backup techniques

As was pointed out above, typically the biosphere is not able to fix so much oxygen or nitrogen that it would change the atmospheric concentrations of these gases too much. However, to facilitate dealing with accident scenarios like air leakages or atmospheric poisonings, having compressed or liquefied O_2 and N_2 available could be desirable [5]. If so, it may make sense to also have a mechanism available for moving O_2 and N_2 selectively from the habitat into the tanks by e.g. cryogenic distillation of air [11]. If such process is implemented, then CO_2 is also separable. For managing CO_2, such process would be energetically inefficient because e.g. to reduce the CO_2 concentration into one half, one has to process 50 % of the air by liquefaction, separating out the CO_2 and returning the O_2 and N_2 back into the settlement. However, if energy is available, energy efficiency is not a requirement for backup strategies. Chemical scrubbing of CO_2 into amines or hydroxides is another possible backup strategy for emergency removal of CO_2. Table 1 lists these alternatives and their potential issues.

5. Discussion

As described in Section 2, gardens, vivariums and other widespread examples of semi-closed (i.e., only gases exchanged) ecosystems show that closed biospheres are feasible. The only issue is to maintain the right atmospheric composition, but this is only a technical problem to which there are many solutions. The

[5] In addition, one probably wants to divide the settlement into separately pressurisable sectors [5] so that people can be evacuated from a sector that suffered an accident.

Table 1: Some alternatives of habitat CO_2 control.

Method	Potential issues
Biomass burning	–Smoke –Need to handle fire
Cryo-distillation or air	–Power-intensive –Reliability concern/moving parts –Mass overhead of CO_2 tanks
Scrubbing into amines or hydroxides	–Reliability concern/moving parts –Safety concern due to chemicals

biomass burning is one of them. The complexity of biology cannot spoil the feasibility of closed biospheres. If it could, it would already have been seen in gardens and vivariums. The complexity of biology is factored out of the feasibility equation.

The biomass burning method works, as such, only in a tropical climate with no dark season. During dark season photosynthesis is stopped and the level of CO2 would probably build up too high in the atmosphere. Therefore, if seasons are wanted, one has to use sectoring such as discussed in Janhunen [5]. Different sectors must then be phased in different seasons and air must be exchanged between sectors.

Biomass burning seems to be a straightforward, scalable, low-tech and reliable solution. A possible drawback is the production of smoke. As on Earth, plants and soil are absorbers of air pollution, but production of smoke should nevertheless be minimised to prevent health issues. In addition, smoke in a settlement environment is more harmful than on Earth, because the settlement has windows through which sunlight enters, or if it is artificially lighted, the lamps have cover glasses. The production of smoke can be minimised by technical means such as igniting the fire by a biogas flame or by mechanically making the biomass into pellets or other granular form.

Biomass burning involves fire, and fire is in principle a risk because conflagration in a space settlement would be very dangerous. Concerning fire risk in general, it is not feasible to eliminate it entirely by removing all possible ignition sources, e.g. because electric equipment is necessary and malfunctioning electric equipment is a potential ignition source. The risk of wildfire can be lowered by having frequent artificial rain so that the environment is fresh and green. Lush nature also boosts agricultural output and is good for aesthetic reasons. However, not everything can be humid since the stored biomass must be dry in order to burn cleanly. Thus the relative humidity should be less than 100 %, which is also convenient for people. To reduce the fire risk further, an easy way is to store the dry biomass far from the locations where it is burned. Artificial rain or sprinkler system must be possible to turn on quickly in case a fire breaks out.

Also other approaches for reducing the fire risk are possible. For example, one can freeze-dry the biomass and store it in a refrigerated space. Storage under nitrogen-enriched atmosphere is another possibility, which eliminates the fire risk during storage. Nitrogen-enriched gas can be made e.g. by filtering air through certain polymeric membranes.

The methods discussed in this paper do not involve moving materials through airlocks. Thus there is no issue of losing atmospheric gases into space.

After O_2, N_2 and CO_2 are controlled, the remaining issue is how to keep the level of other volatile compounds low. Plants remove harmful impurities [10], but they also produce some volatile organic compounds (VOCs) of their own, such as isoprene and terpenes. This smell of plants can be experienced e.g. in greenhouses and it is generally considered pleasant. However, too much of a good thing is potentially a bad thing, so let us briefly discuss loss mechanisms of VOCs. It is thought that the hydroxyl radical OH is an important “detergent” of the troposphere that oxidises VOCs [14]. On Earth, the primary formation of OH is by solar UV and is highest in the tropics where the solar zenith angle is smallest, the stratospheric ozone layer is thinnest and the humidity is highest [14]. Thus, in the settlement it might be a good idea not to filter out the solar UV entirely, but let a small part of it enter so that the UV radiation level mimics the conditions in Earth’s troposphere, thus maintaining some OH to remove VOCs and also methane by oxidation.

One of the referees pointed out that the carbon stock of soil might potentially grow in time due to incomplete decomposing. While certain biomes like some wet peatlands exhibit slow continuous carbon accumulation, typical biomes such as forests have moderate carbon stocks [8] that presumably have not essentially grown even in millions of years. Earth’s significant fossil coal deposits are thought to have been accumulated before lignin-degrading organisms developed around the end of the Carboniferous period [15]. On modern Earth, termites are good lignin decomposers [16] so their presence in the habitat ecosystem could be beneficial for efficient carbon circulation.

6. Summary and conclusions

Controlling a habitat's carbon dioxide level is a nontrivial problem because the atmospheric volume per biosphere area is typically much smaller than on Earth. The problem is important because too low CO_2 ($\lessapprox$ 300 ppmv) slows down plant growth and thus food production while too high concentration ($\gtrapprox$ 2000 ppmv) begins to cause health problems for people.

The problem can be solved by biomass burning. In particular, agricultural waste is a necessary byproduct of food production. One can dry and store this biomass and burn some of it when the CO_2 level in the settlement's atmosphere drops too low. The method is straightforward, robust and low-tech. It ensures large control authority of the CO_2 while keeping the O_2 partial pressure unchanged. The method scales to habitats of all sizes.

In the initial growth phase of the biosphere, one can obtain the CO_2 by burning sugar or carbon. They can be sourced from carbonaceous asteroid materials so that bootstrapping the biosphere does not require lifting large masses from Earth.

Closed ecosystems in habitats are feasible. We know this because there are many examples of semi-closed ecosystems such as gardens – and because it has been done e.g. in Biosphere-II and BIOS-1, 2 and 3[17]. Maintaining the atmosphere is an engineering problem that can be solved. For gases other than CO_2, the problem is in fact solved automatically. For the control of CO_2, the biomass burning method seems simple and effective.

7. Acknowledgement

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References

[1] Bar-On, Y.M., R. Phillips and R. Milo, The biomass distribution on Earth, Proc. Nat. Acad. Sci. 115 (25) (2018) 6506–6511. https://www.pnas.org/content/pnas/115/25/6506.full.pdf

[2] Sullivan, M.J.P., J. Talbot, S.L. Lewis et al., Diversity and carbon storage across the tropical forest biome, Scientific Reports 7 (2017) 39102. https://www.nature.com/articles/srep39102

[3] O'Neill, G.K., The colonization of space, Physics Today 27 (9) (1974) 32–40.

[4] O'Neill, G.K., The high frontier, New York (1977) 288.

[5] Janhunen, P., Natural illumination solution for rotating space settlements, NSS Space Settlement J. (2018). https://space.nss.org/media/NSS-JOURNAL-Natural-Illumination-for-Rotating-Space-Settlements.pdf

[6] Wikipedia article on biomass (ecology), https://en.wikipedia.org/wiki/Biomass_(ecology)

[7] Ricklefs, R.E. and G.L. Miller, Ecology (4th ed.), Macmillan (2000), 192.

[8] Wang, Y.P., R.M. Law and B. Pak, A global model of carbon, nitrogen and phosphorus cycles for the terrestrial biosphere, Biogeosci. 7 (2010) 2261–2282.

[9] Jewell, W.J. and L.S. Valentine, Biological processes in closed ecosystems, Space Manufacturing 14, Space Studies Institute, Oct. 29–31 (2010). http://ssi.org/2010/SM14-proceedings/Biological-Processes-in-Closed-Ecosystems-Jewell-Valentine.pdf

[10] Wolverton, B.C., A. Johnson and K. Bounds, Interior landscape plants for indoor air pollution abatement, Final report, NASA-TM-101766 (1989). https://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/19930073077.pdf

[11] Soilleux, R.J. and S.D. Gunn, Environmental control and life support (ECLSS) for large orbital habitats: ventilation for heat and water transport and management, NSS Space Settlement J.(2018). https://space.nss.org/media/NSS-JOURNAL-ECLSS-for-Large-Orbital-Habitats-Ventilation-and-Heat-Transport.pdf

[12] Thomson, H. and C. Liddell, The suitability of wood pellet heating for domestic households: a review of literature, Renewable and Sustainable Energy Rev. 42 (2015) 1362–1369.

[13] Misra, M.K., K.W. Ragland and A.J. Baker, Wood ash composition as a function of furnace temperature, Biomass and Bioenergy 4, 2 (1993) 103–116.

[14] Lelieveld, J., F.J. Dentener, W. Peters and M.C. Krol, On the role of hydroxyl radicals in the self-cleansing capacity of the troposphere, Atmos. Chem. Phys. 4 (2004) 2337–2344. https://www.atmos-chem-phys.net/4/2337/2004/acp-4-2337-2004.pdf

[15] Floudas, D., et al., The Paleozoic origin of enzymatic lignin decomposition reconstructed from 31 fungal genomes, Science 336 (2012) 1715–1719.

[16] Butler, J.H.A. and J.C. Buckerfield, Digestion of lignin by termites, Soil Biology and Biochemistry 11 (1979) 507–513.

[17] Salisbury, F.B., J.I. Gitelson and G.M. Lisovsky, Bios-3: Siberian experiments in bioregenerative lif support, BioScience 47 (1997) 575–585.