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Abstract

Ecosystems in space will need in-situ bioavailable nutrients. The measured nutrients in meteorites allow experiment-based estimates of nutrients in asteroids, and of the biomass and populations that can be derived from these in situ bioresources. In this respect, we found that carbonaceous chondrite meteorites can support microorganisms and plant cultures, suggesting that similar asteroid materials are also biologically fertile. The sustainable biomass and populations are determined by the available resource materials, their yields of nutrients and biomass, the biomass needed to support human populations, the duration of the ecosystem, and wastage. The bioavailable C, N, and electrolytes in carbonaceous chondrite meteorites vary as CM2 > CR2 > CV3 > CO3 > CK4 > CK5 in correlation with petrologic type, including aqueous alteration.Their average bioavailable C, N, K and P can yield 2.4, 3.5, 2.5, and 0.08 g biomass/kg resource material, respectively, showing phosphorus as the limiting nutrient. On this basis, soluble nutrients in a 100 km radius, 10^{19} kg resource asteroid can sustain an ecosystem of 10^{8} kg biomass and a human population of 10,000 for $>10^{9}$ years, and its total nutrient contents can sustain a population of one million, by replacing a wastage of 1% of the biomass per year. Overall, the total nutrient contents of the 10^{22} kg carbonaceous asteroids can yield a biomass of 10^{20} kg that supports a steady-state human population of one billion during the habitable future of the Solar System, contributing a time-integrated biomass of 10^{22} kg-years. These astroecology estimates use experimental data on nutrients in asteroids/meteorites to quantify the sustainable biomass and human populations in this and similar solar systems.

Keywords: astroecology, asteroids, biomass, meteorites, Solar System, space settlements

Highlights:

- Soluble, bioavailable organic carbon and electrolytes were determined in carbonaceous chondrite meteorites.
- Similar nutrients in asteroids offer resources for biology and ecosystems in space settlements.
- Analysis of meteorite nutrients allows experiment-based, quantitative estimates of the potential biomass that can be derived from asteroids resources, to support sustainable astroecology and populations in space settlements.
- In-situ bioresources in asteroids can support human populations of billions through the habitable lifetime of the Solar System.

1. Introduction

Human expansion in the Solar System has been contemplated for over a century since Tsiolkovsky, and it is a long-term goal of NASA ((Rynin, 1971; O'Neill, 1974, 1977; McKay et al., 1991; Sagan, 1994, O'Keefe, 2002; Griffin, 2014). Astroecology experiments with carbonaceous meteorites showed that microorganisms, plant cultures and shrimp hatchlings can grow on these materials (Mautner 2002a, b) Therefore biological materials for space-based ecosystems and human populations can be derived from these in-situ asteroid resources (Mautner, 2002a,b, Montague et al., 2012), similarly to in situ resource utilization (ISRU) for industrial and structural materials. (O'Leary, 1977; Matloff et al., 2001; Bolonkin, 2013)

Carbonaceous C-type asteroids can be physically accessible in-situ biological sources of organics and electrolytes, provide soils for agriculture and extracts for hydroponics, produce food for settlements on the asteroids or on terraformed planets and space colonies. (Sears, 1973; O'Neill, 1974, 1977; Bunch and Chang, 1980; Ming and Henninger, 1989, Lewis, 1993; Brearley and Jones, 1998; Dyson, 2000)

Although large populations can be accommodated by space resources, there has been few experiment-based tests whether these resources can support biological growth, or data for estimating potential yields of biomass. Concerning asteroid resources, it is necessary to establish the soil fertilities of model carbonaceous meteorites. For these purposes, agricultural soil fertility tests (McLaren and Cameron, 1996) were miniaturized for the available sub-gram meteorite samples. (Mautner et al., 1995, 1997, Mautner 1997, 1999) These bioassays showed that the Murchison CM2 and Allende CV3 carbonaceous chondrites contain bioavailable, soluble organic carbon and electrolytes including nitrate and phosphate. The small hydroponic cultures supported bacteria, algae, asparagus and potato cultures, and brine shrimp. This soil fertility ranking showed that the fertilities of carbonaceous chondrite materials are similar to productive terrestrial soils. Martian meteorites were also fertile due to their high extractable phosphate. These bioassays confirmed that C-type asteroid materials can contribute significantly to early and future life in the Solar System. (Mautner 2002a,b, 2005, Mautner and Sinaj, 2002, Kennedy et al., 2007)

To evaluate space development quantitatively, it is necessary to assess the biomass, ecosystems and populations that can be derived from asteroid resources. Such quantitative estimates can be obtained from the bioavailable nutrient contents in carbonaceous meteorites, that represent their parent C-type asteroids.

In addition to CM2 and CV3 materials tested before, resources may be obtained also from other types of asteroids. In this respect, tests showed that stony-iron asteroids/meteorites also support autotrophic plant cultures. (Marcano et al., 2005) In order to adapt to these in-situ resources, genetically engineered organisms may be designed to develop microbial communities. (Mautner et al., 1997, Olsson-Francis et al., 2009; Montague et al., 2012)

The present paper surveys nutrient contents in various carbonaceous chondrite meteorites. Combining these data and the elemental compositions of dry biomass, (Bowen, 1966) allows calculating the biomass and populations that can be derived from asteroids. In turn, this information can be combined with estimates of the total mass of asteroids, and of the expected habitable timespan of the Solar System (Lewis 1973, 1977), to assess the biomass and human populations that can be sustained by asteroids here and eventually in other solar systems, such as the water-containing asteroid observed recently about the white dwarf star DG 61. (Farihi et al., 2013)

Beyond biological resources, biomass and populations in space depend on many factors, such as meteorite mineralogy and organic contents, that may affect extraction; also in situ resources for habitats; human and materials transport; and energy sources. These subjects require research beyond the scope of this paper, but the quantitative estimates of the large scope of life in space may encourage more such research.

2. Materials and Methods

Water-soluble materials were extracted from hand-ground meteorite powders. The particle sizes in the powders were mostly in the 1 – 5 micron range with a smaller fraction up to 40 microns, with particle sizes comparable to terrestrial soils.

Samples of 25 mg of the meteorite powders were placed in 0.5 ml deionized water at solid/solution ratios (w/w) of 1:20 and extracted at 20 C for 4 days, or under mild hydrothermal sterilizing conditions at 121 C for 15 minutes. All extractions and analytical measurements were performed in four replicates.

For total C, 10 – 20 mg meteorite powders were combusted at 1000 °C in an oxygen atmosphere in an automated Dumas style elemental analyzer which was linked to a 20-20 PDZ Europa stable isotope ratio mass spectrometer (Crewe, UK). For 22 pairs of duplicate experiments, the average stds as percentage of the measured values were, for total C, 13.4%, and for N, 12.1%, see Table 1. Total N was also analyzed by the Europa mass spectrometer. The extracted C and N were obtained from the difference in C content between the unextracted meteorites and the remaining solids after extraction.

Anions in the meteorite extracts were analyzed by ion exchange chromatography using a Dionex DX-120 Ion Exchange Chromatograph fitted with a Dionex AS50 Autosampler and integrated by Chromeleon Peaknet 6.0. The system is suppressed with an Anion Self-Regenerating Suppressor (ASRS-Ultra) and detection is by conductivity. Cations were analyzed using a Waters Non-Suppressed Ion Exchange Chromatograph and Waters Baseline 810 software with conductivity detection. Samples analyzed in this manner are filtered through a 0.2μm membrane filter prior to analysis. The average standard deviations of all the four replicate experiments for extracted anions and cations was 20% which can be considered as the uncertainty of the values. However, the standard curve calibrations of the measured concentration have minimum values below which larger uncertainties may apply. Under our extraction conditions of 25 mg solids in 0.5 ml water, these lower limits of accurate measurements translate to measured extractable contents in the solids of < 0.04 g/kg for all cations, except 0.02 g/kg for NH_4^+ and < 0.04 g/kg for Cl^- and Br^-, and < 0.01 g/kg for Nitrate-N, Phosphate-P and Sulfate-S. The similar chemistry of NH_4^+ and K^+, (Meot-Ner et al., 1996) may allow interference between these ions in chromatography, but the chromatographic peaks of all the other cations were well resolved.

Samples of Murchison and Allende were gifted by the American Museum of Natural History and from the Victoria Museum of Australia, or obtained from commercial sources. These samples were collected originally from observed falls and are not significantly weathered. The Antarctic meteorite samples were donated by NASA, with the classification and weathering status (A = minor rustiness; B = moderate rustiness; C = severe rustiness; e = evaporate minerals visible to the naked eye): ALH 83102, CM2, B/Ce; GRA 95229, CR2, A; ALH 84028, CV3, Ae; ALH 83108, CO3, A; ALH 85002, CK4, A; EET 92002, CK5, A/Be. In the present and previous work, Allende and Murchison samples were obtained from various sources, and may have originated from different meteorite fragments, but the resulting extracts were generally consistent. The soluble materials are distributed homogenously in the meteorites at the present level of resolution, and they are not affected significantly by handling. Also, extraction yields at 20 C to 120 C and under air or CO_2 were generally similar and consistent (Mautner 2002a,b).

3. Results and Discussion

3.1. Carbon and Nitrogen

Measurements were performed on C and N in the unprocessed and in the extracted meteorites. The results are summarized in Table 1 with the meteorites listed in the order of decreasing total C content. The difference between the contents of the unprocessed and extracted meteorites yielded the extracted amounts.

The concentrations of total C in these meteorites range from over 20 g/kg in CM2 to minor amounts in the CK meteorites. (Cronin and Chang, 1993). In three of the first four high-C meteorites in Table 1, 15 - 20% of the total C was dissolved by water, and this did not vary significantly between extractions at 121 C for 15 minutes or at 20 C for 4 days.

The present results are comparable to a previous extensive study of the hydrothermal extraction of organic C and N from the Murchison meteorite. The total C and N, and their extracted fraction at 120 C were similar to those in Table 1. In comparison, up to 50% of C and 30% of N were extracted at 350 C, and over 90% of C and N removed by dry pyrolysis at 550 C (Mautner et al., 1995) Such high-temperature extractions can be useful for in situ resource utilization, to increase the biomass and populations by up to a factor of 5 over the 20 C yields considered below.

The total and soluble C in the various meteorites can be compared in Table1. While the total C is similar in the two CM2 meteorites, the fraction of soluble C is higher by a factor of 11 in Murchison vs. ALH83012, and soluble N is also significantly higher. Similar but smaller differences in extractable C and N apply between the two CV3 meteorites Allende and ALH84028. In contrast to soluble C and N, the soluble electrolytes are similar in the two CM2 meteorites and also in the two CV3 meteorites.

These differences between the two CM2 and the two CV3 meteorites may indicate different processing in the parent asteroids, such as different heating with the loss of volatile organics. If this variability proves general, asteroid carbon sources will need to be tested individually for soluble carbon.

However, the variability in soluble C may be of terrestrial origin, since Murchison and Allende were collected soon after impact while the Antarctic ALH meteorites were long exposed to weathering. Leaching of soluble materials could have occurred by heating of the dark material by solar radiation, leading to liquid water that can transport solutes from the meteorite. However, the soluble electrolyte contents other than C and N, even of the highly soluble Na and K, are comparable between Murchison and ALH83012, and also between Allende and ALH84028 (Table 2). This does not support significant leaching of these Antarctic meteorites. Other terrestrial weathering could occur by microbial degradation or assimilation of the organic carbon that could make it insoluble.

Interestingly, the soluble element contents, including C and N in the GRA95229 Antarctic CR2 meteorite are also high, although lower by a factor of 2 – 3, compared with Murchison, and the soluble elements in the CO_3 meteorite ALH 83108 are comparable to Allende. These soluble contents in Antarctic meteorites show that leaching and weathering loss of soluble C, if it occurs, is not universal in Antarctic meteorites. The other Antarctic meteorites in this study have too little soluble elements for weathering information.

In any case, terrestrial weathering does not apply to in situ resource utilization, but it is pertinent to using meteorite models. Therefore it is preferable to use samples from fresh meteorite falls for these models.

The soluble contents of hydrous CM and CR meteorites are higher by one to two orders of magnitude than in the anhydrous CV, CO and CK meteorites, in parallel with aqueous alteration. The hydrous CM and CR meteorites contain clays with high cation exchange capacity (Mautner, 1999), that can retain anions and cations, some of which can be released by extraction.

Overall, the present results show significant variation of soluble contents within and among meteorite classes. This is of interest in relation to in situ bioavailable resources, to the development of asteroids, to terrestrial weathering, and possibly to meteorite classification. For these reasons, soluble electrolytes in meteorites justify further studies.

3.2. Soluble nutrients, meteorite soils, and pore solutions

Table 2 lists the concentrations of the water-soluble electrolytes in the meteorite solids. Comparing the extractions for 15 minutes at 121 C or for 4 days at 20 C, the high-temperature extraction dissolved about 20% more electrolytes, but mostly within experimental uncertainty. Table 2 lists the concentrations of the electrolytes in the meteorite materials that are extracted by the 4-day, 20 C extractions. In comparison, Table 3 lists the total elemental contents. Total soluble C and electrolytes show a general correlation (Table 2). Both are highest in the two CM2 meteorites that contain similar concentrations of soluble electrolytes, but soluble C is much lower, apparently anomalously, in ALH83102 than in Murchison.

The main soluble cations are Na^+, Ca^{+2} and Mg^{+2} and NH_4^+, and the main anions are SO_4^{2-} and Cl^- The main soluble ions are highest in the CM2 meteorites, show intermediate concentrations in the CR2 meteorite, and low concentrations in the other meteorites. Sulfate is higher by a factor of 10 – 20 than chloride in the first three high-carbon meteorites in Table 2, but comparable to chloride in the other, low-carbon meteorites.

The biologically important nitrate and phosphate are present in much smaller concentrations than sulfate and chloride, and their concentrations make them the biologically limiting nutrients (see also Table 4).

Interestingly, the concentration of soluble NH_4^+ and K^+ are similar in all the meteorites, although the sources and the cosmic abundances of N and K are different. In this regard, the chemistry of NH_4^+ and K^+ are similar in many respects due to their similar ionic radii. (Meot-Ner et al., 1996) Therefore NH_4^+ and K^+ could have been retained similarly in clays and minerals in the parent asteroids.

The soil pH in the meteorite extracts (usually 20 mg meteorite powder/ ml H_2O) is between 6.2 - 6.9, within the optimal slightly acidic to near neutral range of 5.5 - 7.0 for agricultural soils. This is important for phosphate that does not form insoluble compounds, especially with Ca, in this pH range, and remains biologically available. (McLaren and Cameron, 1996).

The properties of these asteroid fluids, reconstituted from the soluble contents in meteorites, will be presented in detail elsewhere.

The concentration of total carbon and nitrogen are highest in the CM2 and CR2 meteorites (Table 1) which are also highest in soluble cations and sulfate and chloride, (Table 2), and also have the highest degree of aqueous alteration (Barber, 1981, Browning et al., 1996). The correlation of electrolytes and aqueous alteration suggests that the electrolyte salts were dissolved from the minerals during aqueous alteration, and then deposited as evaporates when the water adsorbed into the hydrated minerals. (Tomeoka and Buseck, 1985, Fredrikkson and Kerridge, 1988, Bodnar and Zolensky, 2000, Cohen and Coker, 2000.) Aqueous processes could also transform carbon to soluble organics, yielding the high soluble carbon concentrations in CM2 and CR2 meteorites. The low soluble carbon in the ALH83102 CM2 meteorite may be due to different reasons, including terrestrial processing as discussed above.

3.3. Potential biomass

The preceding sections demonstrated bioresources in asteroids materials, that can be used as soils for agriculture, or as extracts for hydroponics. (O'Neill, 1974, 1977, Sagan, 1994; Ming and Henninger, 1989; Lewis, 1993) The potential yield of biomass can be calculated from the compositions of the resource materials, compared with the requirements of biological tissues. Applications of the biomass in turn depend on its efficiency to support human populations, and on the rate of wastage that depletes the resource and affects the life-span of the ecosystem.

The information in Tables 2 and 3 can be used to calculate the biomass that can be constructed from the soluble or total bioresource contents of carbonaceous asteroids.

The biomass ($m_{biomass}$) that can be obtained from the resource materials is calculated from equation (1) using the concentration of element x in the resource material ($c_{x,resource}$) and in dry biomass ($c_{x,biomass}$). Equation (1) can be applied to soluble components in the resource materials, if $c_{x,resource}$ represents the soluble components, or to total elemental contents of the resource materials, if $c_{x,resource}$ represents these components. (The yield of $m_{biomass,x}/m_{resource,x}$ in units of g biomass/kg resource material is obtained by the multiplier 1,000 in the rhs)

$$m_{biomass,x} = 1000\ m_{resource,x}\ c_{x,resource} / c_{x,biomass} \qquad (1)$$

Applying equation (1) to each element x yields the amount of biomass ($m_{biomass,x}$) that could be constituted from the resource material if a given nutrient x was the limiting component. The element that yields the smallest biomass is the limiting element. Table 4 shows these results for each element in each meteorite, and also for the biomass derived from a composite soil with the average soluble contents and also from the average total contents of nutrient elements in these meteorites.

For the present calculations we use for $c_{x,resource}$ the average concentrations of soluble elements in the present meteorites (Table 2, row 9) or total elemental contents (Table 2, row 10), and for $c_{x,biomass}$ the average of the concentrations of elements in the dry biomass of bacteria, brown algae, angiosperm plants and mammalian tissues (Table 2, row 11 (Bowen, 1966)). The results in Table 4 show that the yield of available $m_{biomass,x}$ per unit $m_{x,resource}$ is smallest for P, making it the limiting element in the soluble contents of all of the meteorites. The next smallest biomass yields would be those based on C, N and K. The meteorite soils are similar to terrestrial soils where P, N and K also need to be supplemented by fertilizers. Two meteorites contain extractable C below the detection limits, making it the limiting nutrient in these objects.

Applying Equation (1) shows that soluble P in 1 kg resource material allows a yield of 0.06 g dry bacterial biomass from the Murchison meteorite, 0.08 g from ALH83102, 0.03 from GRA95229, 0.19 from Allende, 0.06 from ALH84028, 0.05 from ALH83108, 0.09 in ALH85002, and 0.08 g from EET92002 materials. (Table 4)

The results in Tables 2 and 4 show that various elements in various meteorites are differently effective resources. For example, Allende yields the highest biomass based on bioavailable P, but it is relatively low in C, while Murchison is the opposite. Therefore composite soils from various asteroids may be the most effective for delivering the optimal nutrients to various crops.

Assuming access to various asteroids, the following examples consider a composite soil with the average nutrient contents of the present meteorites. The soluble contents may be obtained from these soils using basic aqueous extraction, or may be extracted from the total contents using more intensive processing. Table 2, data rows 9 and 10 show the average soluble and total elemental contents in the meteorites, and row 11 shows the elemental contents in average dry biomass of bacterial, algal, plant and mammalian tissues (Table 2, row 11). (Bowen, 1966) These data are used in equation (1) to calculate the yield of composite biomass that can be obtained from the composite meteorite soil. In the composite soil P is again the limiting soluble nutrient, that allows 0.08 g biomass per 1 kg resource material, i. e. about 10^{-4} kg biomass/kg resource material using bioavailable soluble contents, as used in the estimates below. Resource material means here the raw native local rock, not the processed extracted nutrients.

3.4. Total elemental contents, and plant micronutrients

In addition to the soluble elements, the total elemental contents of asteroids are also of biological interest. The total contents can be made bioavailable by intensive technologies, to provide more plant macronutrients and essential micronutrients. Table 3 lists the full elemental contents of the present meteorites, which can be compared with the soluble contents (Table 2). Further, Table 5 shows the biomass allowed by the total concentration of each element in each meteorite, that can be compared with Table 4 based on soluble nutrients.

For example, considering composite carbonaceous chondrite soils, the average soluble macronutrient C, N, K and P contents are 1.1, 0.1, 0.085 and 0.0012 g/kg (Table 2, row 9), compared with the average total contents of 7.3, 0.4, 0.6 and 1.2 g/kg, (Table 2, row 10) respectively. This reflects the soluble/total contents in the meteorites, where 15, 25, and 14% of the total C, N, K, but only 0.1% of the total P is soluble. Because of the high total P, it is not the limiting element when the total contents are used. Rather, N and K then become limiting, but they still allow a biomass over 300 times larger than P allows using the soluble contents. The applications below will use a rounded biomass yield of 10^{-4} from the soluble contents and 10^{-2} kg biomass/kg from the total elemental contents of the resource material, that means here the raw native local rock.

Biological matter also requires micronutrients. For plants they include manganese, boron, copper, iron, chlorine, molybdenum, and zinc, which are observed in all of the present meteorites (Table 3, boron and molybdenum were not measured). Unlike the wide range of soluble contents, the heavier elements vary little among the present meteorites. The Fe and Ni contents may be toxic and need to be removed from asteroid soils.

4.1. Parameters for space-based ecosystems

The above results allow a quantitative estimate of the biomass and human populations based on in situ carbonaceous asteroid resources. Data on meteorites give the potential yields of nutrients from respective asteroids, which is then compared with the elemental requirements of biomass. In turn, the estimated yields of biomass ($yield_{mbiomass/mresource}$) are combined with the amounts of asteroid resources to calculate the amount of derivable biomass and its supported populations. These biomass and populations are depleted by irreversible wastage. The wastage can be replaced using nutrients from the resource asteroids to maintain a steady-state biomass and population, but this process depletes and ultimately exhausts the resources. The ecosystem terminates when the resources cannot support further self-reproduction.

Most of the variables in this process are determined by physical factors, but the biomass and lifetime of the ecosystem are interdependent. The biomass can be set to achieve a desired lifetime for the ecosystem, or a desired lifetime can be set to allow a desired population. The relations among these variables are summarized by equations 2 – 4 below, and then applied to various habitats with the results summarized in Table 6 below.

4.2. Relations among resources, biomass and population

Equation (2) gives the total biomass ($m_{biomass,total}$) that can be derived from the mass of the raw resource material ($m_{resoure}$) using their nutrient contents, to form biomass with a yield of ($yield_{mbiomass/mresource}$). This biomass is then lost as wastage during the lifetime of the ecosystem ($t_{ecosystem}$).

$$m_{biomass,total} = m_{resource} \times yield_{mbiomass/mresource} \quad (2)$$

The rate coefficient of wastage ($k_{wastage}$) is a fraction of the steady-state active biomass (percent of $m_{biomass,steady\text{-}state}$) per unit time (year). Therefore the absolute wastage per year is determined by $k_{wastage}$ and the amount of steady-state biomass, according to $k_{wastage} \times m_{biomass,\ steady\text{-}state}$. Over the duration of the ecosystem, the wastage amounts to $k_{wastage} \times m_{biomass,steady\text{-}state} \times t_{ecosystem}$ which is equal to the total amount of biomass ($m_{biomass,total}$) that was constructed from the resource materials according to ($m_{resource} \times yield_{mbiomass/mresource}$).

Since the rate of wastage that ultimately exhausts the resources during $t_{resource}$ is given by $k_{wastage} \times m_{biomass,steady\text{-}state}$, a desired duration $t_{ecosystem}$ can be achieved by setting the steady-state biomass. Conversely, a desired steady-state biomass and its supported population can be achieved by setting $t_{ecosystem}$ such as to allow the desired $m_{biomass,steady\text{-}state}$ (both assuming that the total resource-based biomass and the rate coefficient of wastage $k_{wastage}$ are not variable).

In turn, the steady-state biomass $m_{biomass,steady\text{-}state}$ supports a steady-state population ($n_{population,steady\text{-}state}$) according to the ratio ($r_{support}$) = ($m_{biomass,steady\text{-}state}/n_{population,steady\text{-}state}$), through the duration time $t_{ecosystem}$ of the ecosystem.

These relations lead to equations (2) and (3). Equation (3) results if all the nutrients in the original raw resource are converted to biomass and then to irreversible wastage during the lifetime of the ecosystem.

$$m_{biomass,total} = m_{biomass,steady\text{-}state} \times k_{waste} \times t_{ecosystem}$$
$$= n_{population,steady\text{-}state} \times r_{support} \times k_{waste} \times t_{ecosystem} \qquad (3)$$

In equations (2) and (3) $m_{resource}$, $yield_{mbiomass/mresource}$ and therefore $m_{biomass,total}$, and also $r_{support}$ and k_{waste} are considered as non-variable parameters. Then $m_{biomass,steady\text{-}state}$ (and the resulting $n_{population,steady\text{-}state}$) and $t_{ecosystem}$ are adjustable parameters, where one determines the other according to equation (3). The values of the parameters in equations (2) and (3) are discussed in the next sections.

4.3. Parameters for Sustainable Biomass and Populations

The ecological relations (2) and (3) can yield the amounts of in-situ resources needed to achieve a given total or steady-state biomass and population. The values the other factors in equations (2) and (3) are discussed in the next sections.

4.3.a. Biomass yields and wastage

Table 4 shows the biomass that could be formed from each soluble nutrient in each of the present meteorites if that element was limiting, calculated from equation (1) using the elemental compositions of biomass. (Bowen, 1966) Table 4 also shows the biomass that can be obtained from the average soluble nutrient contents of the present meteorites. This would be dissolved from a composite soil constructed from equal amounts of materials from asteroids similar to the present meteorites. On this basis P is the limiting nutrient in this composite soil, with a yield of 8×10^{-5} kg biomass/kg resource. However, if the total elemental contents of the present meteorites are used, N becomes limiting with a yield of to 5.9×10^{-3} kg biomass/ kg resource (Table 4, rows 9 and 10). Actual yields will depend on the fertilizer needs of crops, the compositions of the soils, and the availabilities of resource asteroids. As noted above, the estimates use rounded $yield_{mresource/mbiomass}$ of 10^{-4} and 10^{-2} kg biomass/ kg raw resource, using the soluble or total nutrient contents, respectively.

The wastage rate k_{waste} is the fraction of biomass lost per unit biomass per unit time, estimated below as k = 0.01/year, i.e., 1% of the active biomass lost irreversibly per year, for example, by mineralization or dispersal in space, during $t_{ecosystem}$, years of the active ecosystem (years).

4.3.b. Sustained populations

The model assumes ecosystems where a steady-state biomass supports a steady-state population. In the terrestrial ecosystem an estimated 10^{15} kg global biomass, (Bowen, 1966) supports on the order of 10^{10} humans, corresponding to 10^{5} kg supporting biomass per human. A more efficient designed ecosystems with selected crops optimized for human nutrition and grown in optimized soils, or in hydroponic or aeroponic cultures, may require less supporting biomass per human. The present model assumes $r_{support} = 10^4$ kg supporting biomass/person.

4.3.c. Time-integrated biomass

To evaluate an ecosystem, it is useful to quantify the overall life that the ecosystem supports during its lifetime. For these purposes, the product $M_{TB} = (m_{biomass,steady\text{-}state} \times t_{ecosystem})$ in equation (2) yields the time-integrated biomass M_{TB} (here in kg-years) in the ecosystem (equation 4a). Similarly, the total number of human-years accumulated by the population may be expressed as n_{int} (person-years) (equation 4b).

$$M_{TB} = m_{biomass,steady\text{-}state} \times t_{ecosystem} \quad (4a)$$

$$n_{int} = n_{population,steady\text{-}state} \times t_{ecosystem} \quad (4b)$$

Note that M_{TB} depends only on the total biomass obtained from the resource and its rate of wastage, as every unit biomass contributes an equal amount of MTB regardless of when it was constructed. Therefore M_{TB} does not depend on the rate of construction of the biomass. This also applies to ecosystems that undergo exponential decay without waste replacement, see below.

4.3.4. Energy requirements

In addition to materials, an ecosystem requires energy consumption, 10 kW per person in present industrial world. The energy requirements and supplies in space need independent studies, but for the present purposes, we need to check if energy is a limiting factors considering the desired biomass and populations.

A solar energy conversion efficiency to electricity of 10% is considered. Assuming an energy demand of industrialized nations on the order of 10 kW per person (1 kW human use and 9 kW for supporting ecosystem), this requires collecting 100 kW solar power per person. The insolation at an inner asteroid belt edge of 2 AU (astronomical units, 1.5×10^{11} m) from the Sun is 0.35 kW/m^2, which then requires collecting, converting to electricity and using solar energy from an area of 286 m^2 per person.

This insolation, generated by the power output of the Sun is 3.8×10^{26} W and at 2AU distributed over a sphere of 1.1×10^{24} m^2 is comparable to the insolation at mid-latitudes on Earth, which is clearly sufficient for plant growth.

At the rate of 100 kW/person, the solar power output could sustain a population of 10^{21} humans in a Dyson sphere that collects and uses all the solar output (Dyson, 1960). This is far larger than the populations that can be sustained by the asteroid biological resources discussed below. Therefore biomaterials, rather than energy, are the limiting factor for human populations based on asteroid in situ resource utilization.

5. Applications for space settlements and populations

This section considers the resource requirements and the amounts of biomass and populations that can be sustained in various settlements using materials from carbonaceous asteroids.

The following sections concern small exploratory outposts with populations of ten, manufacturing bases of one hundred, and urban settlements of a million settlers.

With the parameters discussed above, a population of n settlers requires 10^4n kg supporting biomass with a loss rate of 100n kg/year that is replaced by processing 10^6n kg/year asteroid materials using soluble nutrients, or 10^4n kg/year asteroid materials using total asteroid elemental contents. The biomass of the ecosystem and the human populations remain constant during the lifetime of the habitats. The time-span of initial construction and the wind-down are considered instantaneous compared with the time-span of the ecosystem.

The settlements may be located on the resource asteroids, or in separate space colonies, or on moons and planets that import asteroid-based biological resources. Space transport requirements can be minimized if the nutrients are extracted on the resource asteroids, reducing the transported mass to a few percent of the original rock mass. Also, the overall mass of the resource asteroid remains nearly unchanged by the extraction.

The populations are sustained by in situ resources that replace irreversible wastage of the biomass. The estimates illustrate the upper limits of sustainable populations from these resources. More limiting constraints may be imposed by energy, materials transport, safety, economy, psychology and social factors, but these will need separate studies.

The present paper considers only the constraints due to bioavailable in-situ nutrients. These estimates should evolve with further data about asteroid numbers, masses, and compositions. Beyond the numerical results, the sections below illustrate the application use of meteorite data to obtain for such estimates. These estimates use the parameters discussed above, that are summarized in Table 6.

5.1. Ecology of exploratory outposts

An exploratory outpost with a crew of ten may use resources from an accessible 10 km radius, 10^{16} kg carbonaceous asteroid similar in size to Phobos, (Pang et al., 1978) and assumed in Table 2 to have the average composition of the present meteorites. With a basic agriculture using soluble materials that yields 10^{-4} kg biomass/kg resource material, this resource can then yield 10^{12} kg biomass.

Using the parameters in the preceding sections, the crew of ten in a self-sustaining base will require 10^5 kg supporting active biomass. This will lose 1%, i.e., 10^3 kg/year to waste, that can be replaced using soluble nutrients from 10^7 kg/year asteroid materials. The 10^{12} kg asteroid-based biomass can provide this replacement for 10^9 years.

The replacement biomass of 10^3 kg/year can be derived by processing 10^7 kg/year asteroid materials kg/year (27 tons/day) that may be prohibitive at this stage. However, this amount is based on soluble P as the limiting nutrient. If nutrients are produced from the total rock contents then N becomes limiting and the yield increases by a factor of 100 as discussed above. The processing requirements can then be reduced to a more practical 10^5 kg/year (i.e., 270 kg/day). With these parameters the 10^{16} kg resource asteroid could sustain the 10 person crew for 10^9 years using soluble asteroid materials, or 10^{11} years using the total nutrient contents, much longer needed for exploratory bases.

The power consumption of the outpost, based on 100 kW per person, is 1,000 kW insolation that can be collected at 2AU from a 2860 m^2 i.e., a 53x53 m solar collector.

The parameters for the exploratory base are summarized in Table 6, first data row.

5.2. Construction bases

Expansion in space may proceed to intermediate-sized construction bases for larger colonies. These bases will require self-sustaining ecology and manufacturing, on the scale of 10,000 settlers.

The settlement may use resources from a 100 km radius, 10^{19} kg C-type asteroid such as Aurora (average diameter 197 km). Desirable features would be low density such as Mathilde (1.3 g/cm^3) that indicates a loose rubble pile structure (Housen et al., 1999) which facilitates processing, or an icy asteroid or dwarf planet such as Ceres (mean radius 950 km, mass 9.4×10^{20} kg) that can provide water (Kuppers et al., 2014).

A construction base on Aurora may be used, and equations (3) and (4) can estimate the sustainable populations. Assuming the average composition of meteorites in Table 2, soluble materials of this asteroid can yield 10^{-4} kg biomass/kg resource, providing 10^{15} kg biomass that can be used to replace irreversible wastage. If the settlement is to survive on these resources for 10^9 years, then 10^6 kg wastage of biomass/year can be replaced, that requires processing 10^{10} kg/year asteroid materials. At the rate of wastage of 0.01 kg/year per kg biomass, this can replace wastage produced by 10^8 kg steady-state biomass. If 10^4 kg biomass supports a human, this resource supports a steady-state population of 10,000 settlers for a billion years, using the materials of a 10^{19} carbonaceous asteroid. (Table 6, data row 2) Using the total elemental contents of the asteroid with a yield of 0.01 kg biomass/kg resource, and the asteroid can then support a million settlers for 10^9 years.

At 286 m^2 solar energy collector per settler as above, the 10,000 settlers will require power collection over 2.86×10^6 m^2 i.e, a feasible 1.7km x 1.7km collection area. Therefore energy is not a limiting factor.

Beyond serving as a manufacturing base, such settlements can serve a "Noah's Ark" to secure human survival through the habitable lifetime of the Solar System, should the Earth become inhospitable. Larger populations may be desirable but they could deplete asteroid resources too fast, unless wastage is further reduced significantly.

5.3. Urban settlements

Major space colonies of million-scale populations have been considered in detail, and are aspirational goals for space advocates (O'Neill 1973, 1977). The colonies may be free standing, or built on large C-type asteroids such as Hygiea (average diameter 431 km), or on Mars using carbonaceous asteroid materials for soils and organics. A population of one million using the resources of the previous 100 km, 10^{19} kg asteroid will be considered.

With the above parameters, the 10^6 inhabitants will require 10^{10} kg supporting biomass that loses 10^8 kg/year to waste, which can be replaced using the total elemental contents of 10^{10} kg/year (27 kg/day per settler) asteroid materials.

At this rate, materials from the 10^{19} kg asteroid can support the population for 10^9 years. However, natural agriculture using soluble nutrients would require processing 10^{12} kg/year asteroid materials (2,700 kg/day per settler), and the resources could support the populations then for 10^7 years. At this rate the resource would support the population only for 1% of the habitable lifetime of the Solar System.

With the energy parameters used above, the population of a million requires 10^8 kW collected over 2.8×10^8 m^2 (17 km x 17 km) equivalent to 0.2% of the resource asteroid surface. Satellite solar power systems may be also employed.

5.4. Ecology without waste replacement

Alternatively to maintaining a modest steady-state population in the above examples, the full amount of extracted bioresource materials in all the asteroids may be converted rapidly to biomass, producing 10^{20} kg biomass that allows a supported population of 10^{16} in principle. As noted above, other technological, biological, economic and psychological and social factors may be more limiting, and therefore these are upper limits of populations. Without resources for waste replacement, the biomass and population would then diminish exponentially due to 1%/year wastage with a rate coefficient k = 0.01, losing 0.01 x $m_{biomass}$ kg per year.

The biomass then decays exponentially as in equation (5) with a half-life of $t_{1/2} = (\ln 0.5)/k$.

$$m(t) = m_o e^{-kt} \quad (5)$$

Here m_o and m(t) are the biomass after time 0 and time t, respectively, where a fraction k_{waste} of the biomass is lost to waste per year. Equation (6) then yields the time-integrated biomass from initial construction to time t.

$$M_{TB} = \int_o^t m(t)dt \quad (6)$$

The total time-integrated biomass is given by integration from t = 0 to ∞, even given a finite t_{limit} since from then on the biomass is zero. For exponential decay as in equation (5), the time-integrated biomass from t = 0 to ∞ is then simply $M_{TB} = m_o/k_{waste}$ (kg-years).

An ecosystem may terminate at time t_{limit} when the biomass is reduced to m_{limit} below which the population cannot reproduce, for example, to 10^4 kg biomass that supports one remaining human. With the above parameters, if the 10^{22} kg asteroid materials yield 10^{20} kg biomass that supports 10^{16} humans, a 1% wastage/year would reduce this biomass to the last 10^4 kg that supports the last human, in only 3,684 years.

Starting with the 10^{20} kg biomass, the time-integrated biomass is then $m_o/k_{waste} = 10^{20}/0.01 = 10^{22}$ kg-years, including 10^{18} human-years during its 3,684 year life-span. This time-integrated biomass is equal to that obtained above by smaller steady-state 10^{13} kg biomass that sustained 10^9 humans for 10^9 years.

The time-integrated biomass depends only on the total amount of biomass and its rate of decay. However, for ethical reasons, society may wish that life will continue as long as possible, which is achieved by a reduced biomass and reduced waste.

Optimally, if waste is eliminated completely, the entire bioresource may be converted to biomass rapidly and survive indefinitely. Mathematically, any finite biomass in a permanent ecosystem would then produce an infinite time-integrated biomass.

6. Implications for early life

Nutrient resources in carbonaceous chondrite asteroids can contribute to life in early solar nebulae. For example, liquid water in the pores asteroid rocks during aqueous alteration can contain organics and electrolytes at high, several mol/L concentrations, which can allow complex organic chemistry. Porosities of 15 – 25% (Macke, 2010) of carbonaceous chondrites allow asteroids to contain large volumes of nutrient pore solutions.

For example, soluble organics and electrolytes reach several molar concentrations in pore solutions of the Murchison CM2 meteorite. (Mautner 2002a, b) Such concentrated solutions can be trapped along with mineral catalysts in early asteroids. In $4 – 6x10^6$ years of aqueous alteration, (Guo et al., 2007) this allows multi-step chemical synthesis of thousands or up to millions of steps, leading to complex biopolymers. This supports suggestions that microbial life started in asteroids. (Chyba and McDonald, 1995; Pizzarrello, 2006) The microorganisms in these environments may be anaerobic halophiles tolerant to Ca and Mg sulfates.

Bioavailable nutrients in a large asteroid can then yield enough microbial populations, that, if scattered in the asteroid belt, can seed the 10^{22} kg of asteroids and possibly comets, some of which are ejected to interstellar space. Nutrients in meteorite fragments of these objects can yield enough microorganisms to colonize a planet in this or other solar systems. (Mautner, 2002a, b)

Quantitatively, a 10 km radius, $4x10^{12}$ m^3 and 10^{16} kg asteroid with 20% porosity would contain $8x10^{14}$ L pore solutions with 10^{13} kg organic C (using 1.1 g/kg soluble C, Table 2), and the total 10^{22} kg asteroids would contain 10^{19} dissolved organic C, in 0.01 kg/L (about 0.1 mol/L) solutions. A Myear of aqueous conditions, and reactions with half-lives of seconds to years, allow multi-step chemical synthesis of $10^6 – 10^{13}$ steps, to build up complex self-catalytic protein or RNA polymers, leaving a further 4 – 6 Myears of aqueous conditions for prebiotic chemistry to progress toward microbial life. Similar processes can occur later in the pores of carbonaceous chondrite meteorites that land on planets and are exposed to water. (Mautner 2002a, b).

The data on soluble nutrients and derived biomass (Tables 2 - 4) suggest that, based on P, Murchison-like C-type asteroids can then yield about 10^{-4} kg biomass/ kg resource material. The above 10 km, 10^{16} kg early asteroid could yield a bacterial dry biomass of 10^{12} kg comprised of 10^{29} microorganisms. Scattered in the asteroid belt, this could provide 10^7 inoculant microorganisms/kg asteroid to colonize the 10^{22} kg asteroids in the early Solar Nebula. Similarly, microorganisms in a 10 kg meteorite of Murchison-like composition could reach a biomass of 1 g with a population of 10^{14} microorganisms, sufficient to inoculate the planet. Further, soluble materials in the 10^{22} kg asteroids can yield a microbial biomass up to 10^{18} kg comprising 10^{35}

microorganisms, that could in principle inoculate 10^{11} solar systems in the galaxy each with 10^{24} microorganisms.

In summary, based on biological resources alone, microbial populations derived from a meteorite can inoculate a planet, an asteroid can inoculate the asteroid belt, and microorganisms formed from nutrients in an asteroid belt could inoculate the galaxy. However, other factors may limit these processes.

7. Upper limits of asteroid-based ecology

The upper limits of biomass and populations based on carbonaceous asteroids are determined by the total nutrient element contents of the estimated 10^{22} kg mass of these asteroids.

Using the soluble or total nutrient contents with a $yield_{mbiomass/mresource}$ of 10^{-4} or 10^{-2} kg biomass/kg resource, the 10^{22} kg carbonaceous asteroid mass yields a total biomass of 10^{18} or 10^{20} kg, respectively. When used to replace biomass waste at the rate of 0.01 $m_{biomass,steady-state}$/year for 10^9 years, this allows, according to equation (3), a steady-state biomass of 10^{11} or 10^{13} kg, respectively, supporting a steady-state human population of 10^7 or 10^9 through this billion year time-span (Table 6, data row 6). Further, soluble or total materials in the 10^{26} kg comets would sustain a steady-state population of 10^{11} or 10^{13} during a billion future years of the Solar System. (Mautner, 2005)

In terms of total time-integrated biomass, the upper limits of 10^{13} kg asteroid based, or 10^{17} kg comet-based steady-state biomass for 10^9 years produce a time-integrated biomass M_{TB} of 10^{22} or 10^{26} kg-years, respectively, supporting 10^9 or 10^{13} humans for 10^9 years, yielding a time-integrated 10^{18} or 10^{22} kg-years, respectively. In comparison, a human life can contribute 100 human-years, and therefore the population of the Solar System can experience 10^{16} human lives or 10^{22} human-years, using the total asteroid or cometary materials as in-situ space resources, respectively.

Considering energy requirements, based on an industrialized 100 kW power per person, the steady-state population of 10^9 or 10^{13} requires 10^{14} or10^{18} W, a small fraction of the 3.8×10^{26} W output of the Sun. Considering the power demand of the biomass, the estimated 10^{15} kg terrestrial biomass is supported by 3×10^{16} W adsorbed solar irradiance (240 W/m^2 absorbed irradiance x 1.3×10^{14} m^2 Earth cross section), i.e., 30 W/kg biomass. At this rate, the maximum 10^{20} kg biomass allowed by the total asteroid contents would require a solar power supply of

$3x10^{21}$ W, only about 10^{-5} fraction of the solar output. The 10^{26} kg materials in comets could yield a biomass larger by a factor of 10^4, with a solar power demand of $3x10^{25}$ W, closer to the total solar output that can be collected by a Dyson sphere (Dyson, 1960)

According to these considerations, the biota and population of the Solar System are limited by materials rather than energy. However, on cosmological scales, as radiative energy declines, life can become energy-limited. Altogether, mass and energy resources allow 10^{22} kg-years of asteroid-based and 10^{26} kg-years comet-based biological life in the Solar System, compared with 10^{48} kg-years of potential biological life in the galaxy (Mautner, 2005)

8. Conclusions

Total and water-soluble C and N and soluble electrolyte contents were measured in several types of carbonaceous chondrite meteorites. Among various classes of meteorites, the concentrations of the soluble electrolytes in the solids correlate with the extent of aqueous alteration and with the total carbon contents, consistent with the formation of soluble organics and electrolytes by aqueous processes in early asteroids.

Further, the soluble organic carbon and electrolytes show that pores of early asteroids could contain concentrated several molar solutions of organics and salts, that allow multi-step synthesis of organics, macromolecules and possibly microorganisms.

The observed correlations between soluble C, electrolytes and degree of aqueous alteration can make the soluble electrolytes useful in classifying meteorites. This may be practical for complementing transmission IR spectroscopy and other methods related to aqueous alteration. (Beck et al., 2014) Soluble electrolytes can be measured readily by common laboratory methods using milligram samples that are usually affordable even for destructive extractions.

The data on bioavailable nutrients can be combined with elemental concentrations in biological tissues, for an experiment-based estimate of biomass and populations formed from, and sustained by, carbonaceous asteroid materials. For example, soluble, bioavailable nutrients in a 100 km asteroid could sustain a settlement of 10,000, and its full elemental contents can sustain an urban settlement of a million, for 10^9 years.

Extended theoretically to the full Solar System, the total elemental contents of the estimated 10^{22} kg carbonaceous asteroids can yield 10^{20} kg biomass, and given a 1%/year wastage, these asteroid materials can sustain a steady-state biomass of 10^{13} kg that supports 10^9 humans for 10^9 habitable years in the inner Solar System.

These considerations illustrate applications of experimental data, here on bioavailable nutrients in meteorites, for quantitative estimates of potential ecology, biota, and human populations in the Solar System. These estimates suggest that carbonaceous asteroids can sustain extensive life and human populations through the habitable future of the Solar System. Technologies that develop then in space can extend life to new solar systems, where it may advance further using similar asteroid resources.

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Table 1. Total and water-soluble carbon and nitrogen in carbonaceous chondrites

		C [a] Total	C [b] After Extract.	C [c] Extract. % of total	N [a] Total (g/kg)	N [b] After Extrac.	N [c] Extract % of total
Murchison	**CM2**	21.7	17.0	22	0.99	0.84	15
ALH 83102	**CM2**	17.1	16.8	2	0.67	0.64	5
GRA 95229	**CR2**	11.7	9.8	16	0.94	0.68	28
Allende	**CV3**	4.8	3.8	20	0.42	0.29	30
ALH 84028	**CV3**	2.0	2.5		0.067	0.033	51
ALH 83108	**CO3**	0.78	0.75	99	0.055	0.019	65
ALH 85002	**CK4**	0.71	0.52	26	0.063	0.014	77
EET 92002	**CK5**	0.28	0.29	0	0.11	0.010	91

a. Concentrations of C or N in meteorite (g/kg). Estimated uncertainties from the average stds of four replicates as percentage of the values reported in the Table: For C, 13.4%; for N, 12.1% of the reported values. b. Remaining C or N content (g/kg) after extraction at solid/solution ratios of 1:20 at 20 C for 4 days. c. Percent of original C or N content removed by water extraction.

Table 2. Water-soluble contents in carbonaceous chondrites (g element/kg solid)[a]

		C[b]	N[b]	Na^+	K^+	Mg^{2+}	Ca^{2+}	NH_4^+	Nitrate-N	Phosphate-P	Sulfate-S	Cl^-	Br^-
Murchison	CM2	4.8	0.15	2.17	0.24	2.57	2.93	0.30	0.008	0.0010	6.09	0.35	0.0092
ALH 83102	CM2	0.3	0.03	5.03	0.24	2.75	3.47	0.29	0.003	0.0012	8.07	0.33	0.0015
GRA 95229	CR2	1.8	0.26	1.43	0.13	0.79	0.59	0.19	0.008	0.0005	2.06	0.16	0.0010
Allende	CV3	1.0	0.12	0.07	0.03	0.10	0.08	0.04	0.004	0.0030	0.18	0.09	0.0000
ALH 84028	CV3	0.0	0.03	0.22	0.01	0.18	0.12	0.02	0.017	0.0010	0.29	0.08	0.0003
ALH 83108	CO3	0.8	0.04	0.31	0.017	0.09	0.13	0.03	0.044	0.0007	0.29	0.16	0.0004
ALH 85002	CK4	0.2	0.05	0.05	0.004	0.18	0.13	0.01	0.046	0.0014	0.37	0.07	0.0002
EET 92002	CK5	0.0	0.10	0.08	0.008	0.16	0.20	0.01	0.006	0.0012	0.49	0.04	0.0025
Average Extractable Element[c]		1.1	0.10	1.17	0.085	0.85	0.96	0.11	0.017	0.0012	2.23	0.16	0.0019
Average Total Element[d]		7.3	0.40	4.7	0.6	146	15			1.2	1.7	0.49	
Average Element in Dry Biomass[e]		462	67	12.9	34.4	3	21	67	67	15.5	7.4		

a. All units are g(element)/kg solid. Data for Allende and Murchison average from previous measurements (Mautner, 1997, 2002a,b, Mautner and Sinaj, 2002). Data for the other meteorites are results from present extractions at solid:solution ratios of 1:20 g/mL at 20 C for 4 days. Estimated uncertainties, from the average stds of duplicate measurements, are 20% of the reported values. Larger uncertainties may apply when the extractable contents are <0.04 g/kg for all ions, except < 0.02 g/kg for NH_4^+; and < 0.04 g/kg for Cl^- and Br^-, and 0.01 g/kg for Nitrate-N, Phosphate-P and Sulfate-S. b. Soluble, presumably organic C and N. c. Average concentration of each element in the present meteorites, from the present data. d. Total concentration of the element in each meteorite (unpublished results), averaged over the present meteorites. e. Average concentration of each element in dry biomass of bacteria, brown algae, angiosperm plants and mammals. (Bowen, 1966)

Table 3. Total concentrations of elements in carbonaceous chondrites [a]

	C[b]	N[b]	Na	K	Mg	Ca	P	S	Al	Si	Ti	Cr	Mn	Fe	Co	Ni	Cu	Zn	Cl
Murchison	21.7	0.99	4.4	0.69	152	13	0.95	25	14	153	0.62	3.3	1.7	180	0.57	11	0.16	0.11	0.52
Murchison[c]	19.1	0.96	4.0	0.4	126	13	18	1.0	13	127	0.59	3.1	1.8	205	0.58	12	0.15	0.19	
ALH83102	17.3	0.65	7.2	0.75	130	13	1.00	30	12	141	0.89	3	1.5	214	0.8	14	0.35	0.12	0.86
GRA95229	11.5	0.93	5.5	0.78	165	15.5	0.85	17	20	186	0.70	3.5	1.7	129	0.38	6.5	0.1	0.12	0.42
Allende	4.8	0.42	3.8	0.86	137	14	1.05	15	20	155	0.64	3	1.5	215	0.77	10	0.09	0.13	0.25
ALH84028	2.1	0.04	2.9	0.19	152	16	1.45	15	16	152	0.50	3.4	1.3	207	0.6	12	0.17	0.18	0.01
ALH83108	0.8	0.05	5.8	0.57	148	14	1.20	6.7	18	157	0.67	3.3	1.8	218	0.47	9.4	0.16	0.13	0.19
ALH85002	0.2	0.06	4.2	0.49	148	18	1.25	15	19	148	0.82	2.9	1.6	208	0.72	17	0.07	0.1	0.50
EET92002	0.2	0.04	3.6	0.56	138	20	1.45	15	24	146	1	3	1.8	214	0.65	16	0.18	0.11	0.72

a. Units of g/kg. From XRF measurements on 100 mg grounded meteorite powders with a PW2404 Dispersive X-Ray Fluorescence Spectrometer and SuperQ 3.0k with IQ+, FPMulti, TCM2404 and TDS2404 software with IQ+ fundamental parameters method, from PANalytical (formerly Philips Analytical X-Ray) Corporation. Calibration with NIST-certified soils and comparisons with literature values for Allende and Murchison (see footnote c) suggests an uncertainty of ±10% except for P where the results were scaled by 0.5. b. Values for C and N from Table 1. c. Literature values for comparison. For C, N, Si, P, S, Ti and Cu from Jarosewich (1971) and from Fuchs et al. (1973) For other elements from Rubin et al. (2007). The ratio for Murchison (NIST)/Murchison literature for all the elements is average = 1.01, stdev = 0.30. Differences between the present and literature data reflect the uncertainties in both sources, and inhomogeniety of the meteorite.

Table 4. Biomass yields from water-soluble elements in carbonaceous chondrite materials[a]

		C	N	Na^+	K^+	Mg^{2+}	Ca^{2+}	NH_4^+	Nitrate-N	Phosphate-P	Sulfate-S
Murchison	**CM2**	10.3	2.2	168	7.0	856	140	4.4	0.1	0.06	823
ALH 83102	**CM2**	0.7	0.5	390	7.0	917	165	4.4	0.0	0.08	1091
GRA 95229	**CR2**	4.0	3.8	111	3.8	262	28	2.9	0.1	0.03	279
Allende	**CV3**	2.1	1.9	5	0.8	34	4	0.6	0.1	0.19	24
ALH 84028	**CV3**	0.0	0.5	17	0.3	60	6	0.3	0.3	0.06	39
ALH 83108	**CO3**	1.7	0.5	24	0.5	32	6	0.5	0.7	0.05	39
ALH 85002	**CK4**	0.4	0.7	4	0.1	61	6	0.1	0.7	0.09	51
EET 92002	**CK5**	0.0	1.5	6	0.2	53	10	0.2	0.1	0.08	66
Average Biomass using Extractable Elements[b]		2.4	1.5	91	2.5	284	46	1.7	0.3	0.08	301
Average Biomass using Total Elements[c]		15.9	5.9	362	17.8	48,750	735			74	2,343

a. Units of g biomass/kg meteorite. Maximum biomass (g) of average composition that could be constructed from a given soluble element x in 1 kg of each meteorite, if x was the limiting nutrient. Calculated using Equation (1) and soluble contents from Table 2, and average elemental concentrations in dry biomass $(c_x)_{biomass}$ as in Table 2. b. Calculated using the average extractable elemental concentrations in Table 2 and the average in dry biomass. c. Calculated using the average of the total elemental concentrations in Table 2 and the average in dry biomass.

Table 5. Biomass yields from total elements in carbonaceous chondrite materials[a]

		C	N	Na^+	K^+	Mg^{2+}	Ca^{2+}	P	S
Murchison	**CM2**	47.0	14.8	341.1	20.1	50,666.7	619.0	61.3	3,378.4
ALH 83102	**CM2**	37.4	9.7	558.1	21.8	43,333.3	619.0	64.5	4,054.1
GRA 95229	**CR2**	24.9	13.9	426.4	22.7	55,000.0	738.1	54.8	2,297.3
Allende	**CV3**	10.4	6.3	294.6	25.0	45,666.7	666.7	67.7	2,027.0
ALH 84028	**CV3**	4.5	0.6	224.8	5.5	50,666.7	761.9	93.5	2,027.0
ALH 83108	**CO3**	1.7	0.7	449.6	16.6	49,333.3	666.7	77.4	905.4
ALH 85002	**CK4**	0.4	0.9	325.6	14.2	49,333.3	857.1	80.6	2,027.0
EET 92002	**CK5**	0.4	0.6	279.1	16.3	46,000.0	952.4	93.5	2,027.0

a. Units of g biomass/kg meteorite. Maximum biomass (g) of average composition that could be constructed from a given element x in 1 kg of each meteorite, if x was the limiting nutrient. Calculated using Equation (1) and total elemental contents from Table 3, and average elemental concentrations in dry biomass $(c_x)_{biomass}$ as in Table 2, row 10.

Table 6. Estimated parameters of ecosystems derived from asteroid resources

Settlement type	Asteroid Resource mass (kg)[a]	Biomass yield (kg biomass/ kg resource)[b]	Ecosystem biomass (m_o)[c]	Steady-state ecosystem biomass ($m_{steady-state}$)[d]	Ecosystem biomass waste (kg/year)[e]	Ecosystem Timespan (year)[f]	M_{TB} time-integrated biomass (kg-year)[g]	Population (steady state)[h]	Population time-integrated (person-year)[i]
Exploratory	10^{16}	10^{-4} (soluble)	10^{12}	10^5	10^3	10^9	10^{14}	10	10^{10}
Construction	10^{19}	10^{-4} (soluble)	10^{15}	10^8	10^6	10^9	10^{17}	10^4	10^{13}
Construction	10^{19}	10^{-2} (total)	10^{17}	10^8	10^6	10^{11}	10^{19}	10^4	10^{15}
Urban	10^{19}	10^{-4} (soluble)	10^{15}	10^{10}	10^8	10^7	10^{17}	10^6	10^{13}
Urban	10^{19}	10^{-2} (total)	10^{17}	10^{10}	10^8	10^9	10^{19}	10^6	10^{15}
All asteroid[j]	10^{22}	10^{-2} (total)	10^{20}	10^{13}	10^{11}	10^9	10^{22}	10^9	10^{18}
All asteroid[k]	10^{22}	10^{-2} (total)	10^{20}	10^{20} to 10^4	$0.01*m_{biomass}$	$3.7x10^3$	10^{22}	10^{16} to 0	10^{18}

a. Masses of raw asteroid resource materials used to support settlement bases. 10 km radius resource asteroid, 10^{16} kg; 100 km radius resource asteroid, 10^{19} kg; mass of all carbonaceous asteroids, 10^{22} kg. b. $Yield_{mbiomass/mresource}$ (see eq. (2)) Soluble: based on soluble nutrients; total: based on total nutrient elemental contents. c. Overall biomass derived from the resource base ($m_{biomass,total}$) ($m_{resource}$ x $yield_{mbiomass/mrsoirce}$) (see eq. (2)). d. Steady-state active biomass maintained by waste replacement ($m_{biomass.steady-state}$) (see eq. (3)). e. Biomass waste at 1%/year, (k_{waste} x $m_{biomass,steady-state}$) (see eq. (3)). f. Potential ecosystem timespan ($t_{ecosystem}$) that can be sustained with the stated parameters, using the asteroid resource mass ($m_{biomass,total}$)/(k_{waste} x $m_{biomass,steady-state}$) (see eqs. (2) and (3). g. Time-integrated biomass ($m_{biomass,steady-state}$ x $t_{ecosystem}$) (see eq. 4a)). h. Steady-state population ($m_{biomass,stready-state}$ /$r_{support}$) using $r_{support} = 10^4$ biomass/person (see eqs. (2) and (3). i. Time-integrated population ($n_{population,steady-state}$ x $t_{ecosystem}$ (see eq. (4b)). j. Total nutrient contents of all the asteroids are used to maintain steady-state population with waste replacement. k. Resources of all the asteroids are converted to biomass and decay without waste replacement at the rate of $k_w = 0.01m_{biomass}$/year (see eqs. (5) and (6).