THE SECOND LAW, THE FOURTH LAW, RECYCLING AND LIMITS TO GROWTH

by

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Abstract

Despite counter examples in nature, it has been argued that total recycling is impossible for an industrial society as a consequence of the second law of thermodynamics. In this paper it is shown that there is no such limitation. However, it is also shown that ther must be a large stockpile of inactive materials as well as an exogenous source of exergy (e.g. from the sun) for a stable steady-state recycling system to function.

Introduction

This article is prompted by a recent symposium on the contributions of the late Nicholas Georgescu-Roegen — hereafter G-R for simplicity — to environmental and resource economics. The collection appears in a special issue of the journal *Ecological Economics (1)* 1997, edited by Herman Daly. Georgescu-Roegen's most influential writings appeared from 1971 through 1979*(2)*. It is probably fair to say that G-R was the first economist to recognize clearly the relevance of thermodynamic constraints, especially the entropy law, to economics. This historical point is not in dispute. However there are major controversies on two issues. One is the deceptively simple question: how should these physical laws be applied in economics and to what extent does the entropy law, in particular, impose limits on economic growth? Much has been written on this question, well summarized in recent books and survey articles.*(3)* This was the question that motivated the symposium. I return to it briefly later.

The other subsidiary, but even more controversial, question concerns G-R's assertion of a "fourth law" of thermodynamics, to the effect that perfect recycling is "categorically impossible", whence matter becomes dissipated and unavailable for human use in the same way that the second law prescribes for energy. This proposition appears, at first glance, to be well confirmed by the depletion of natural resources. There are obvious counter-examples in nature: carbon, oxygen and nitrogen are evidently recycled by solar energy. Alvin Weinberg, among others, has noted that useful energy (i.e. exergy) is ultimately the only scarce element because, if enough of it is available, all other elements can be captured and concentrated from the atmosphere, the oceans or the earth's crust.*(4)* G-R argued fiercely against this "energy dogma" (and incidentally attacked the so-called "net energy" school) for espousing it.

As regards the "energy dogma", H.T. Odum, the ecologist, has written *(5)*

> "it is thoroughly demonstrated by ecological systems and geological systems that all the chemical elements and many organic substances can be accumulated by living systems from background crustal or oceanic concentrations without limit as to concentration so long as there is available solar or other source of potential energy"

Indeed, Odum's point about the ability of natural organisms to concentrate chemical elements, and organic compounds, is very pertinent to current consenms about bio-accumulation of so-called persistent organic pollutants (POPs).*(6)*

However, the "fourth law" has no status in physics. More specific criticisms of the so-called fourth law have appeared from a number of physical scientists.*(7)* To be sure, these criticisms seriously undermine G-R's most passionately defended position, and consequently weaken his credibility with respect to the broader issue, viz. how and to what extent thermodynamic constraints may limit economic growth. In some respects, this is unfortunate, because material dissipation does impose real constraints on the economic process. To anticipate the conclusion of this paper, the "fund-flow" framework set forth by G-R in 1979*(8)* can be revised and extended slightly to reflect the reality of physical dissipation without going beyond the established second law.

To recapitulate briefly: G-R's thesis amounted to several non-controversial propositions, and one erroneous implication. Among the generally non-controversial propositions are the following: (1) human welfare is a function of economic output (production); (2) production is inherently material-intensive; (3) material processing requires available energy (i.e. *exergy*); it converts low entropy materials (e.g. fossil fuels, metal ores) into high entropy materials (e.g. wastes); (4) the stockpile of high quality (low entropy) materials, including fuels, on earth is finite; (5) recycling materials or fuels — converting high entropy materials into low-entropy materials — requires an exogenous flow of low entropy energy (i.e. *exergy*) and (6) materials can never be recycled with 100% efficiency because there are always entropic losses.

As is well-known, Georgescu-Roegen and some of his followers have concluded from the foregoing that the economic system is therefore doomed to "run down" as the low entropy *material* resources on earth are dissipated and become unavailable. Daly is the main modern exponent of this thesis*(9)*, although he does not explicitly defend the "fourth law". In this respect, G-R and Daly have both relied largely on semi-empirical arguments about resource depletion.*(10)* Some critics from the physical sciences have accused G-R of simply failing to realize that the earth is not a thermodynamically closed system, and that continuing exergy flux from the sun will suffice to permit materials recycling forever.*(11)* However, this criticism does not fully address his argument.

In fact, G-R argued that perpetual recycling would be impossible, *even if unlimited energy (i.e. exergy) were available*, because of entropic dissipation (proposition #6). He argued that since production requires material and exergy resource inputs, there must be a limit to the potential for economic growth. In recent years this "limits" argument has been refined and restated, especially by Herman Daly.*(12)*

As regards the above list, of course #1 is hardly controversial. The same is true of propositions #3 through #6. However, while proposition #2 is an accurate description of the current economic system it is not necessarily a true description of an ideal future "spaceship" economy. This is because human welfare is attributable in the final analysis to non-material services. In other words, while it is true that some, if not all, services have a material base, *there is no definable upper limit to the service output of a given material product,* thanks to the possibility of dematerialization, re-use, renovation, recovery and recycling.*(13)* Incidentally, this is the strongest argument in defense of Solow-Stiglitz' admittedly oversimplified neoclassical models.

Most important for this paper, what does follow from proposition #6 is the following: even the most efficient conceivable recycling process will generate some high entropy wastes. These wastes will accumulate over time in a storehouse or "wastebasket", which might be the earth's crust, the oceans, or just a tank in a spaceship. It follows further that, in the absence of any further recovery, the useful materials or products in circulation would be diminished in every period by the amount lost to the wastebasket. Under these circumstances the economy would, indeed, "run down" as G-R asserted.

However, there is a fundamental flaw in this reasoning. It is simply that, given the postulated availability of energy (exergy), there is no barrier to treating the "wastebasket" as an ore pile and recovering materials from it. It is true that the secondary recovery process will never be 100% efficient, due to the second law. So there will always be some waste from the recovery process itself. However, this waste merely goes back into the waste basket. But as long as the waste pile is big enough, regardless of grade, it is possible to compensate for the losses. Thus, the correct implication of #6 is just that not all of the materials in the earth (or in a spaceship) can be in "active service" at any given time because the wastebasket can never be eliminated altogether. The size of the wastebasket compared to the size of the active inventory is a function (as will be seen) of the efficiency of recycling, the rate of depreciation and the rate of waste mining. If the exergy flux is limiting (which could be the case) then the maximum sustainable concentration ratio will also depend on the available exergy.

How big a wastebasket?

A different question can now be posed: for a given recycling efficiency, how big must the stock of waste materials be to allow a constant level of "useful" materials in a stable system driven by an unlimited exogenous exergy flux?

To give this model some intuitive verisimilitude, a critical resource in an interstellar spaceship might be copper, or platinum; the active mass might be copper wire, or some catalyst, and the inactive mass might be worn out and discarded electro-mechanical and electronic equipment, or spent catalysts. The point of the argument, in this case, would be that a self-sufficient interstellar spaceship with an infinite energy supply and a very efficient repair/renovation/recycling system on board would still have to allocate some considerable space to storing worn out and broken equipment (junk) for future recycling.

For biologists, the critical resource could be carbon, the active mass might be thought of as the carbon embodied in biomass, while the inactive mass in this case would be humus, dissolved carbonates in the ocean, insoluble carbonates in the lithosphere or carbon dioxide in the atmosphere. Other critical resources might be nitrogen, sulfur or phosphorus. Evidently a truly realistic model would involve a number of critical elements and a number of different sorts of inactive mass.

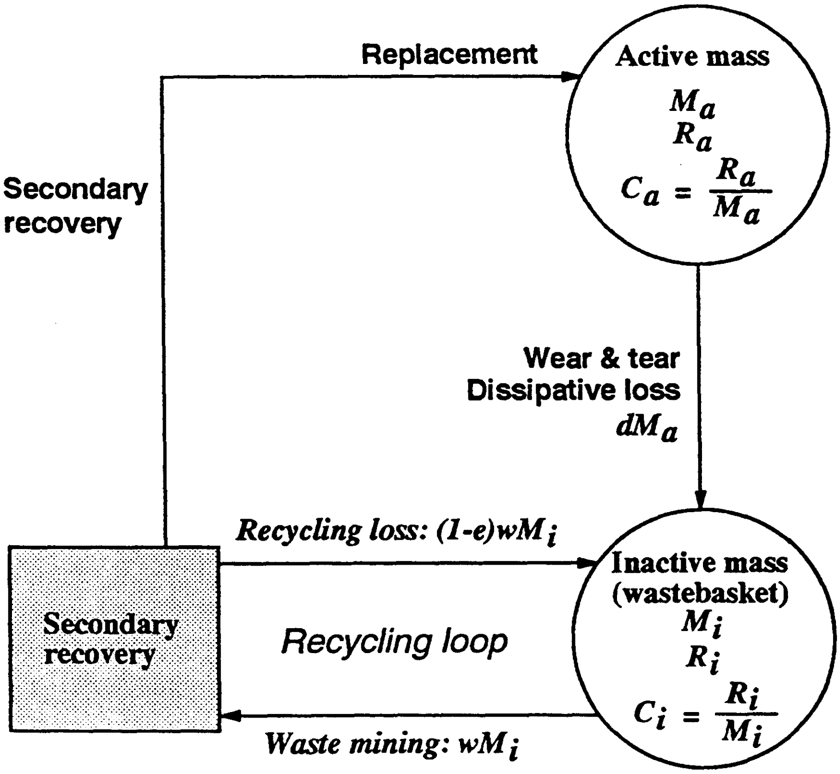

Figure 1. A stable recyling system

The problem can be formulated more rigorously in terms of a simple model, as shown in *Figure 1.* Assume a system in steady-state with both `active' and `inactive' masses, a single critical resource, and a single secondary recovery mechanism. The active mass is in a low entropy state, while the inactive mass (waste) is in a higher entropy state. The active mass — say, the spaceship or the anthroposphere — contains a quantity R_a, of the critical resource, homogeneously distributed (on average) within its mass M_a. It also incorporates an inactive reservoir with mass M_i. and an amount of the critical resource R_i, also distributed homogeneously. (Anticipating a point that arises later, these may be in chemically different forms.) These are extensive variables. There are two corresponding intensive variables, namely the concentration ratios:

$$C_a = \frac{R_a}{M_a} \tag{1}$$

and

$$C_i = \frac{R_i}{M_i} \tag{2}$$

where C_i can be thought of as the "ore grade" of the homogeneous stockpile of waste.

In steady-state, by definition, the quantities of active and inactive resources and masses will be constant and the inflow and outflow of each kind of mass to and from each reservoir must balance. The system is also characterized by four parameters, d, *e*, *f*, *w*. The parameter *d* is the rate of depreciation of the active mass (as a fraction of M_a); it is also the rate of resource loss through dissipative metabolic and other processes, including "wear and tear". Thanks to the second law of thermodynamics, depreciation cannot be zero ($d > 0$). The second parameter *e* is the gross recovery efficiency, i.e. the fraction of the waste mining flux into the secondary recovery unit that is returned to the active mass during the secondary concentration process. The third parameter *f* is the fraction of the critical resource in that gross mass flux that is returned to the active mass from the secondary recovery unit. The last parameter *w* is the rate of mining or recovery from the inactive mass (as a fraction of M_i); *w* can be greater than unity. The second and third of these parameters have values less than unity, as the second law of thermodynamics requires.

There are two balancing conditions, one for gross mass flux one for resource flux. In words, the gross mass and critical resource inputs to and outputs from each reservoir must be equal in a stable steady state. It is easy to verify by inspection that this condition implies whence the ratio of inactive to active masses in steady-state is determined,

$$\frac{M_a}{M_i} = \frac{we}{d} \tag{3}$$

As applied to the critical resource, the balancing condition implies

$$\frac{R_a}{R_i} = \frac{wf}{d} \tag{4}$$

Thus the steady-state concentration ratios for the two masses are determined by the degree of concentration of the critical resource in the secondary recovery (waste mining) process

$$\frac{C_a}{C_i} = \frac{f}{e} \tag{5}$$

Note that this result is independent of the depreciation rate *d*. The concentration of critical resource in the active and inactive reservoirs only differ if *e* and *f* differ. If the recovery rate *f* for the critical resource is lower than the average recovery rate *e* for the 'ore', then the `ore grade' of the inactive mass must be greater than that of the active mass, and *vice versa*.

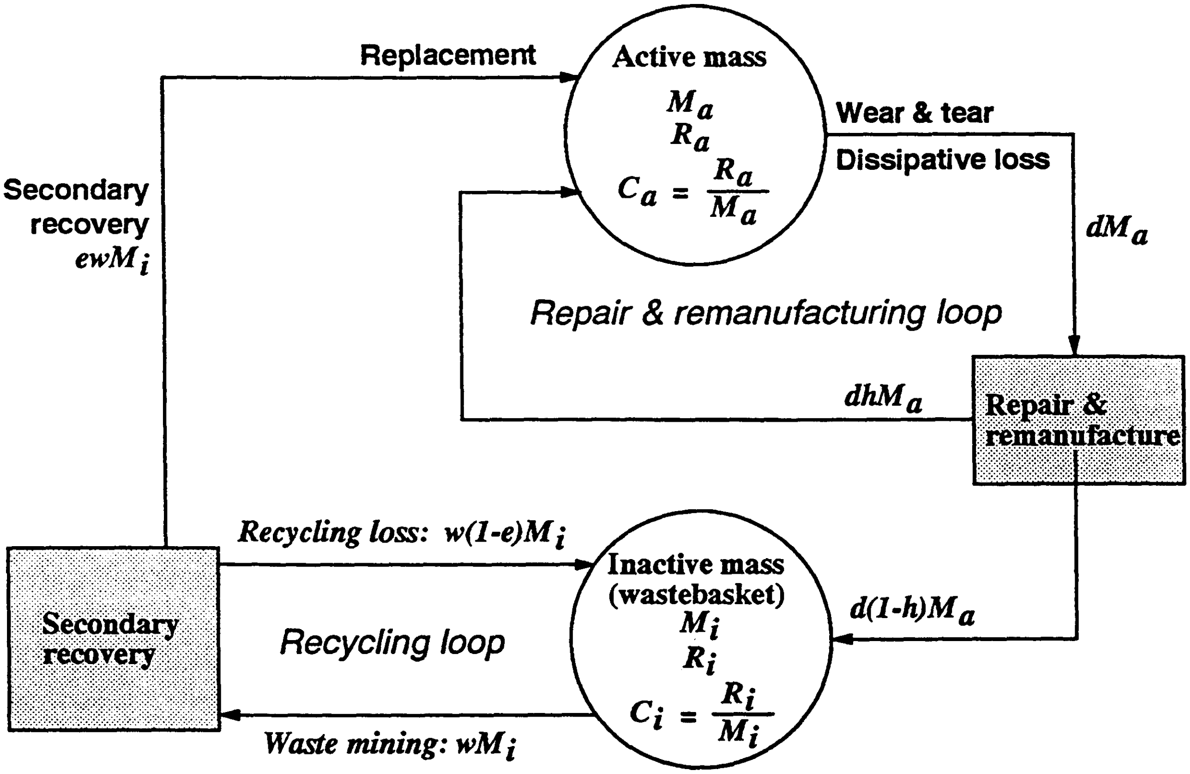

Figure 2. A more complex stable recycling system

If an additional recovery loop is added, as shown in *Figure 2*, the algebra is more complicated, but the result is similar. In this case, two more parameters are needed, namely the fraction *h* of depreciation waste flux that can be recovered and reused, repaired or renovated by physical processes (without being dissipated or chemically transformed) and returned to the larger homogeneous waste reservoir) and the efficiency *k* of recovery of the critical resource from that stream. It is plausible that $k > h$ since the critical resource is presumably more valuable than other mass, and thus justifies greater investment in recovery technology.

Again applying mass balance conditions for both gross mass flux and critical resource flux, and doing some algebra one obtains

$$\frac{M_a}{M_i} = \frac{we}{d(1-h)} \tag{6}$$

$$\frac{R_a}{R_i} = \frac{wf}{d(1-k)} \tag{7}$$

and

$$\frac{C_a}{C_i} = \frac{f(1-h)}{e(1-k)} \tag{8}$$

Note that (6-8) reduce to (3-5) when the additional recycling loop is eliminated, i.e. $h = k = 0$. Evidently the above implies that the quantity of the critical resource in an inactive state R_i *cannot* be zero; in fact, it may be much larger than R_a, especially if w is small and e is near unity. (For intuitive confirmation, recall that the amount of carbon embodied in living biomass is probably exceeded by the amount embodied in dead biomass (humus), and far exceeded by the quantity embodied in atmospheric carbon dioxide, and the vastly larger amount embodied in carbonates.)

Clearly there is nothing to prevent the concentration of a critical resource embodied in active mass to be much higher than its concentration in inactive mass. The additional recycling loop can add to this differential.

Exergy requirements

By definition, the steady-state system cannot gain or lose mass. However, the `metabolism' of the active mass, as well as both recovery loops, are assumed to be driven by an external flux of exergy.*(14)* The exergy requirements X of the system consist of two components, X_1 and X_2. The first term X_1 itself consists of two components: the first is operational (or metabolic) requirements of the active mass; these must be proportional to M_a and thus to R_a. Next there is the *chemical* exergy required to convert the essential resource from its inactive form (in stored waste) to its active useful form, which is also proportional to the loss replacement rate dR_a. Thus $X_1 = aR_a$.

Finally, there is a second term X_2 resulting from the need for physical concentration of the resource in the inactive mass to the concentration required for the active mass. This term compensates for, and is proportional to, the entropy increase resulting from the dissipative loss process. This, in turn, is proportional the mass of resource that is dissipated (i.e. diffused) to the environment as a result of depreciation, metabolic processes and "wear and tear" in the active part of the system. The so-called "ideal gas" approximation for the diffusion term is proportional to the quantity flux dR_a times the natural logarithm of the concentration ratio, or (C_a/C_i). In effect there are two terms with two parameters to be determined, viz.

$$X = R_a\left(a + b\ln\left(\frac{C_a}{C_i}\right)\right) \tag{9}$$

We can solve (9) for the maximum concentration ratio that is attainable in terms of the available exergy flux X, viz.

$$\ln\left(\frac{C_a}{C_i}\right) = \frac{1}{b}\cdot\frac{X}{R_a} - \frac{a}{b} \tag{10}$$

or, exponentiating on both sides

$$\frac{C_a}{C_i} = \exp\left(-\frac{a}{b}\right)\exp\left(\frac{X}{bR_a}\right) \tag{11}$$

where C_a / C_i is given by (8).

Evidently the maximum resource concentration ratio increases as the exponent of the available exergy flux per unit of the resource in its active form. Arbitrarily high steady-state concentration ratios can be attained with the help of a large enough exergy flux.

Conclusions

The real world is obviously far more complex than the two models described above, insofar as it involves more than one critical resource, more than one inactive resource storehouse, and multiple concentration mechanisms. In a real system there will be different constants for each resource, each reservoir and each concentration mechanism. The reservoirs are not homogeneous. The algebra of a more realistic model rapidly becomes intractable.

But there are two key feature of any system that will not change. First, it is *not* possible for all of the critical resource to be utilized actively and also recycled in a steady state system. There must be one (or more) inactive reservoirs or "wastebaskets" for high entropy wastes. Second, in a steady state the active/inactive concentration ratios can be arbitrarily high, depending on the available exergy flux from outside the system.

The most important implication for the real world is that a "spaceship economy" (with total recycling of critical materials) is perfectly consistent with the second law of thermodynamics, provided only that a sufficient exergy flux is available from outside the system, e.g. from the sun. This contradicts G-R's thesis of a `4th law' of thermodynamics and it's suggestion of inevitable decline and collapse, perhaps within a few hundred years.

However, G-R's fund-flow framework for the analysis of a steady-state recycling economy*(15)* is fundamentally faulty. It requires one slight (but critical) modification. The original version defines only three `funds' — corresponding to `factors of production' — namely people, produced capital and Ricardian land. The problem this creates is that recycling is implicitly assumed to be an instantaneous, albeit energy- and resource-consuming, process converting wastes back into recycled active materials. No `fund' (or reservoir) of inactive wastes is allowed.

The analysis in this paper makes it clear that, in practice, there must be such a reservoir of inactive materials. Indeed, because wastes are — by definition — low grade mixtures, the concentration of any given "essential" resource must be low. This implies that the wastebasket of inactive high entropy materials is likely to be very large in mass terms. (This is obviously consistent with the observed situation in the real world, as noted in the Appendix).

More significant in terms of economic theory, if the reservoir of inactive wastes is a `fund' in G-R's terms it would seem to follow that it must also be, in some sense, a factor of production. This raises questions that I leave for consideration in a future paper.

Appendix A: Georgescu-Roegen's Flow-Fund Matrix

G-R has set foth a representation of the economic process in terms of 'flow elements' (which are transformed) and 'fund elements' which are agents of transformation (such as land, tools and workers), themselves unchanged. The scheme is shown in *Table A.1.*

Table A.1: The aggregated economic process

Elements	P_1	P_2	P_3	P_4	P_5
			Flow coordinates		
CE	x_{11}	$-x_{12}$	$-x_{13}$	$-x_{14}$	$-x_{15}$
MK	$-x_{21}$	x_{22}	$-x_{23}$	$-x_{24}$	$-x_{25}$
C	*	*	x_{33}	*	x_{35}
RM	*	$-x_{42}$	$-x_{43}$	x_{44}	*
ES	$-e_1$	*	*	*	*
W	w_1	w_2	w_3	$-w_4$	w_5
DE	d_1	d_2	d_3	d_4	d_5
			Fund coordinates		
Capital	K_1	K_2	K_3	K_4	K_5
People	H_1	H_2	H_3	H_4	H_5
Ricardian land	L_1	L_2	L_3	L_4	L_5

Source: N. Georgescu-Roegen, "Energy Analysis and Economic Valuation" *Southern Economic Journal,* April 4, (1979), p. 1028.

Outflows are positive, inflows are negative. The following explanation is quoted directly from K. Mayumi, "Georgescu-Roegen's `Fourth Law' of Thermodynamics, the Modern Energetic Dogma and Ecological Salvation" pp. 360-361 *(16)*.

P_1: transforms energy in situ (ES) into controlled energy (CE), ultimately resulting in a form of dissipated energy (DE)

P_2: produces maintenance capital (MK)

P_3: produces consumer good (C)

P_4: *completely* recycles the material wastes (W) of all processes into recycled matter (RM)

P_5: maintains the population (H)

In this representation a flow of energy in situ, e_1, is the only environmental support of the economic process. For the aggregated economic process to be reproducible, the following equalities must always hold good on the basis of the conservation laws at the macro-level:

$$d_1 = e_1 - x_{11} \tag{1}$$

$$d_1 = x_{1i} \qquad (i = 2, 3, 4, 5) \tag{2}$$

$$w_1 = x_{2i} \tag{3}$$

$$w_2 = x_{42} - x_{22} \tag{4}$$

$$w_3 = x_{23} + x_{43} - x_{33} \tag{5}$$

$$w_4 = x_{44} - x_{24} \tag{6}$$

$$w_5 = x_{25} + x_{35} \tag{7}$$

On the other hand for our aggregated economic process to be viable, the entire population should be maintained at least at the minimum standard of living, x_{15}^0, x_{25}^0, x_{35}^0. Hence the following inequalities should prevail:

$$x_{i5} \geq x_{15}^0 \qquad (i = 1, 2, 3) \tag{8}$$

The following well know relationships are also satisfied:

$$x_{11} = x_{12} + x_{13} + x_{14} + x_{15} \tag{9}$$

$$x_{22} = X_{21} + x_{23} + x_{24} + x_{25} \tag{10}$$

$$x_{33} = x_{35} \tag{11}$$

$$x_{44} = x_{42} + x_{43} \tag{12}$$

$$w_4 = w_1 + w_2 + w_3 + w_5 \tag{13}$$

$$w_5 \geq x_{25}^0 + x_{35}^0 \tag{14}$$

Inequality (14), in particular, states that material wastes must accumulate as fast or faster than the production of capital goods plus consumer goods.

Given these inequalities, it is evident that the conditions for "complete recycling" would be very hard to satisfy, as Mayumi notes. Unfortunately, neither G-R nor Mayumi distinguished "waste mining" of a large mass of inactive materials from "recycling" with its misleading implication of simultaneity.

Appendix B: On the magnitudes of inactive mass reservoirs

In the case of carbon, the inorganic source for terrestrial plants is atmospheric carbon dioxide (CO_2) which is converted into sugars by photosynthesis. The atmospheric reservoir contains 720 billion metric tons or 720 Pg*(17)*, while terrestrial vegetation embodies 500 Pg, and the annual cycle of uptake by carbon fixation and loss by respiration and decomposition is 120 Pg. For marine vegetation the inorganic carbon reservoir is dissolved carbonate ($CO_3^{=}$) or bicarbonate (HCO_3^{-}), amounting to 38,000 Pg. But this is still much smaller than the reservoir of unavailable carbon in the form of kerogen (10 million Pg) and sedimentary carbonate rocks (100 million Pg).

In the case of nitrogen, annual terrestrial uptake from organic material in the soil is estimated at 1.2 Pg per year compared to annual biofixation and denitrification of the order of 0.14 Pg[13]. The amount of organic nitrogen embodied in living terrestrial biomass (mainly trees) is estimated to be 7.5 Pg.*(18)* In the oceans the internal cycling of organic nitrogen is estimated to be 6 Pg/y, of which 0.6 to 1.0 Pg is embodied in biomass at any one time, while the reservoir of dissolved organic nitrogen compounds in the ocean that are *available* to phytoplankton is estimated at 20 Pg. But that compares to vastly larger amounts of *unavailable* elemental nitrogen in the atmosphere (3.8 million Pg) and even elemental nitrogen dissolved in the oceans (20,000 Pg).

In the case of sulfur, the inorganic source for both terrestrial and marine vegetation is dissolved sulfate ($SO_4^=$) ions. On land these are constantly replenished in groundwater and soil by atmospheric oxidation of volatile sulfur compounds such as hydrogen sulfide, dimethyl sulfide (produced by marine algae) or sulfur dioxide from combustion of fossil fuels. In effect, the reservoir of biologically available sulfur is the ocean, which amounts to 1.6 million Pg) of sulfate, mainly inorganic. By contrast the quantity of sulfur embodied in marine biomass is only of the order of 0.007 Pg and the quantity embodied in terrestrial biomass is only about 0.76 Pg.

Similarly, soluble phosphorus available to phytoplankton in the oceans (as phosphoric acid) amounts to 80 Pg, as compared to only 0.001–0.140 Pg embodied in marine biomass. But 840,000 Pg is to be found in marine sediments (mostly as insoluble calcium phosphate from bones and shells). This is unavailable to plants. Similarly, most of the phosphorus in soils is insoluble and therefore unavailable. Phosphorus embodied in terrestrial biomass is estimated to be 0.3–0.6 Pg (corresponding to an N:P ratio of 13–25).

Two immediate conclusions can be drawn from the above. One is that inactive mass reservoirs associated with the biosphere are of two clearly distinguishable types, viz. available and unavailable to plants. Availability depends on one of two things, either solubility in water or the existence of an evolutionary biochemical mechanism to capture the element from air. Carbon dioxide is available to all green plants, thanks to photosynthesis, whereas nitrogen can only be "fixed" by a small subset of micro-organisms in nature. Sulfur and phosphorus, by contrast, are taken up from the soil dissolved in water.

The other important conclusion is empirical: even the reservoirs of available inactive mass tend to be vastly larger than the active mass (albeit typically much smaller than the reservoirs of unavailable inactive mass). It is likely that an interstellar spaceship capable of internally recycling all critical resources would have to be very large and most of its mass would have to be inactive by design.

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10. This line of argument, popular in the early 1970s, culminated in the famous "Limits to Growth" Report to the Club of Rome: [D. H. Meadows, D. L. Meadows, J. Randers & W. W. Behrens III, *The Limits to*

Growth: A Report for the Club of Rome's Project on the Predicament of Mankind, (Universe Books, New York, 1972)] and the counter-attack by resource economists such as Solow [R. M. Solow, "The Economics of Resources or the Resources of Economics", *American Economic Review* **64**, (1974)] and Stiglitz [J. Stiglitz, "Growth with Exhaustible Natural Resources. Efficient & Optimal Growth Paths", *Review of Economic Studies*, (1974), and "A Neoclassical Analysis of the Economics of Natural Resources", in: V. Kerry Smith, Ed., *Scarcity & Growth Reconsidered*, Resources for the Future, Washington DC, (1979)]. The special issue of *Ecological Economics*, cited previously, was partly, if not mainly, motivated by G-R's "unanswered" critique of the neo-classical models developed by Solow, Stiglitz and others: [N. Georgescu-Roegen, "Comments on the Papers by Daly and Stiglitz", in: V. Kerry Smith, Ed., *Scarcity & Growth Reconsidered*, Resources for the Future, Washington DC, (1979)] and Herman Daly's challenge: [H. E. Daly, *op cit*, *Toward a Steady State Economy*, W. H. Freeman & Company, San Francisco, (1973)].

11. B. A. Månsson, *op cit* "Thermodynamics & Economics" in: S. Sieniutycz & Peter Salamon, Eds., *Finite-Time Thermodynamics & Thermoeconomics* (Series: Advances in Thermodynamics **4**), (Taylor & Francis New York Inc., New York, 1990), pp.153-174.

    — *op cit* "Recycling of Matter" *Ecological Economics* **9**, 191-192 (1994).

12. H. E. Daly, *op cit*, *Toward a Steady State Economy*, W. H. Freeman & Company, San Francisco, (1973).

    H. E. Daly, *op cit*, "Is the Entropy Law Relevant to the Economics of Natural Resource Scarcity? Yes, Of Course It Is!", *Journal of Environmental Economics & Management* **23**, 91-95 (1992).

13. R. U. Ayres & A. V. Kneese, *op cit* "Externalities: Economics and Thermodynamics" in N. Archibugi & P Nijkamp, Eds., *Economy and Ecology: Towards Sustainable Development* (Kluwer Academic Publishers, The Netherlands 1989).

14. In the current system most of the exergy needed for metabolic purposes is obtained by burning fossil fuels, which are themselves extracted from the environment. However this is not a sustainable situation in the long run since the fossil fuel `stockpile' is finite.

15. N. Georgescu-Roegen, *op cit* "Energy Analysis and Economic Valuation" *Southern Economic Journal*, April 4, 1053-1058 (1979).

16. K. Mayumi, "Georgescu-Roegen's `Fourth Law' of Thermodynamics, the Modern Energetic Dogma and Ecological Salvation" in L. Bonati, U. Cosentino, M. Lasagni, G. Moro, D. Pitea, & A. Schiraldi, Eds. *Trends in Ecological Physical Chemistry*, (Elsevier, Amsterdam, 1993).

17. One million metric tons (10^{12} gm) is defined as a teragram or Tg. One billion metric tons (10^{15} gm) is called a petagram, or Pg.

18. This is a matter of interpretation, since most of the mass of a tree is essentially dead wood. The only truly "living" parts of the tree are the outer layers (e.g. cambium and leaves). Much the same can be said of a coral reef, which is mostly non-living skeletal material of dead organisms. Only the surface layer is living.