An Alternative Approach to the
Economic Evaluation of Resource Amenities

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Problem Statement

We are all shareholders of Earth Inc., an incredibly beautiful dissipative structure exquisitely designed to produce ever-increasing complex forms of life. In reviewing the annual reports we realize that production is faltering and returns are dropping, perhaps to the point of dissolution. Apparently, the availability of critical resource inputs coupled with the over-production of a particular product line are to blame. Naturally, we seek to remedy both situations.

A little silly perhaps, but the analogy above does highlight the realities of our planetary state in 2011--we are short on resource amenities and long on humans. I am exceedingly grateful to the growing community of economists who have joined with ecologists, climate scientists, agronomists, social justice advocates, and many others to try to correct the imbalances. Economists, through the lens of economic development, have provided absolutely critical pieces of the corrective puzzle; namely, that our planet offers us both natural resource commodities and natural resource amenities; two very different but related items of value. And while our economic systems handle the former very well, such economic systems have virtually excluded the latter. Economists are now struggling to somehow include resource amenities (the host of ecosystems services that have thus far been available as public goods) into economic evaluations. This is tough work but absolutely necessary.

Researchers in economics thus far have tried to assign monetary value to resource amenities through a variety of what I will call *secondary techniques* -- techniques that start from the premise that economic value is a function of human culture. For example, the usefulness of willingness to pay (WTP) analysis is that WTP is a function of consumer sovereignty. But consumer sovereignty is an artifact of cultural activity and thus WTP (in all of its various forms and amendments) is a secondary technique because it is premised on the fact that human culture engages in economic activity. Secondary techniques applied to resource amenity valuation include the travel cost method, the total economic value method (with its subset of use values and non-use values), contingent value methods, conjoint analysis methods, hedonic price methods, and combined, stated and revealed preference methods. Even direct valuation through the market is a secondary technique.

Theoretical Basis for the Alternative Approach

The alternative approach below allows researchers to develop *primary techniques* – techniques for estimating the value of resource amenities that start from the premise that the economic value of the environment is a function of humans as biological organisms embedded in the biosphere. The tenets for the alternative approach are as follows:

1. Human beings themselves are, as biological organisms, the link between ecology and economics. As organisms they participate in biogeochemical cycles; as citizens they participate in economic cycles.

2. A single human being is an organism that requires three (very) basic inputs (oxygen, water, and photosynthetic carbon) and produces three (very) basic outputs (carbon dioxide, waste water, and fecal carbon). These biological inputs and biological outputs can be quantified per capita and directly related to quantified amounts of the ecosystem goods and services needed to produce the inputs and recycle the outputs. A variety of simplifying but credible assumptions can be made.

3. A single human being "works" (in both the economic and the physical sense of the word) thereby generating labor capital. This total work is made possible because of the energy transfers between the human being (as an organism) and its environment. This total work can be quantified and directly related to a quantity of money earned. Again, a variety of simplifying but credible assumptions can be made.

4. By 2. and 3. above, the total quantity of resource amenities used (per capita) can be set equal to the total quantity of money earned by work (per capita). Resource amenities can be directly monetized (per capita) because the energy of the entire system is conserved (per capita). Conservative system dynamics, equations, and relationships can thus be applied.

A "Straw-Man" Calculation

The "straw-man" calculation that follows applies tenets 1- 4 (above) to give a rough estimate of the monetary value of one year's worth of oxygen for an average person in the U.S. The value of one year's worth of oxygen is then applied as an ecosystem service of urban trees and the actual ecosystem service value per urban tree is determined. The rationale used to generate the various values in the calculation are documented as the calculation proceeds. Note that uncertainty is expressed with significant figures throughout the calculation and final values are in bold.

Ecosystem Services – The six basic inputs and outputs for human biological support (tenet 2 above) are reduced to three (3) ecosystem services: 1) gas exchange (oxygen and carbon dioxide), 2) water, and 3) waste decomposition (liquids and solids).

Rationale:

1. Oxygen and carbon dioxide are stoichiometric equivalents in the reversible chemical reaction of photosynthesis <----> respiration so counting one will automatically count the other,

$$6CO_2 + 6H_2O \;\text{<---->}\; C_6H_{12}O_6 + 6O_2$$

2. Humans and green plants are mutual symbionts with regard to gas exchange: green plants absorb carbon dioxide and produce oxygen; humans absorb oxygen and produce carbon dioxide.
3. Photosynthetically-derived organic molecules (carbohydrates) are provided to the vast majority of US citizens by agriculture, not natural ecosystems, and so is not considered an ecosystem service.

Human Oxygen Consumption - Human beings, like all other animals, are complex, dissipative structures that are maintained far from thermodynamic equilibrium by the constant input of the solar energy that is captured by plants in the form of photosynthetically-derived organic molecules. That is, human beings obtain their bioenergy from the oxidation of organic molecules using atmospheric oxygen. This processes, respiration, includes the cellular production of adenosine triphosphate (ATP; the body's energy currency) in the mitochondria (the tricarboxylic acid or the Krebs cycle) as well as the macroscopic process of taking in oxygen from the environment and returning carbon dioxide to it (Curtis 1983; Zubay 1983). The consumption of atmospheric oxygen during respiration is a function of numerous other functions including:

- level of physical activity (energy expenditure)
- cardiovascular size and health
- general health
- body weight
- age and sex

Because the level of physical activity is the dominant variable in determining the rate of oxygen consumption, physiologists have developed the metabolic equivalent of task (MET) -- the ratio of work metabolic rate to a standard resting metabolic rate of 1.0 (4.184 kJ) kg^{-1} h^{-1} . Equivalently, MET is expressed as 3.5 ml O_2 kg^{-1} min^{-1} (= 0.210 L O_2 kg^{-1} h^{-1}). 1.0 MET is the energy used (or oxygen consumed) obtained during quiet sitting; the resting metabolic rate. The Compendium of Physical Activities (Ainsworth et al 2000) classifies specific physical activity by rate of energy expenditure (MET values). The Compendium lists MET values that range from 0.9 MET (sleeping) to 18 MET (running at 10.9 mph).

Calculation of Oxygen Consumption Per Year Per Capita - The following equation defines the amount (kg) of oxygen consumption per year per capita for US citizens. This equation is notated as $f(O_2)$.

$$f(O_2) = [\text{Av. Daily Level of Physical Activity}]*[\text{Conversion Factor 1}]*[\text{Body Weight}]*[\text{Duration of Activity}]*[\text{Conversion Factor 2}]$$

$$f(O_2) = \{[(0.9\ \text{MET})(8\ \text{h}) + (3.5\ \text{MET})(8\ \text{h}) + (2.0\ \text{MET})(8\ \text{h})]/24\ \text{h}\}*[0.210\ \text{L},O_2\ \text{kg}^{-1}\,\text{h}^{-1}\text{MET}^{-1}]*[80\ \text{kg}]*[8760\ \text{h yr}^{-1}]*[1.43\ \text{E-3 kg},O_2\,\text{L}^{-1}]$$

= (2.13 MET)*(0.210 L,O_2 kg^{-1} $h^{-1}$$MET^{-1}$)*(700800 kg h yr^{-1})*(1.43 E-3 kg,O_2 L^{-1} ,O_2)

= 448 kg O_2 yr^{-1} per capita

= **400 kg O_2 yr^{-1} per capita**

Rationale:

1. Daily Level of Physical Activity --- 8 h of sleep at a low level of activity (0.9 MET), 8 h of work (at a moderate level of activity (2.5 MET), 8 h of home life / free time at a low moderate level of activity (2.0 MET) (Ainsworth et al 2000).
2. Body Weight --- Taken as the average of the mean weight of men (86.8 kg) and the mean weight of women (74.7 kg) 20 – 74 years of age (Ogden et al 2004).
3. Duration of Activity --- The daily level of physical activity is applied to every day of the year.
4. Conversion Factor 2--- Using the Ideal Gas Law (PV = nRT), standard conditions of pressure (1 atm) and temperature (273 K), and the molar mass of diatomic oxygen (32 g mol^{-1}) the density of oxygen is given as 1.43 E-3 kg L^{-1}.

Calculation of Per Capita Income – The following is an average 2009 per capita income for US citizens. This equation is notated as f($).

f($) = ($32,597 yr^{-1} per US female householder + $48,084 yr^{-1} per US male householder) / 2

= **$40,340 yr^{-1} per capita**

Rational:

1. Income data are for 14.8 million female, family householders (no husband present) and 5.6 million male, family householders (no wife present) as reported in 2009 (US Census Bureau, 2010).

Value of Oxygen as an Ecosystem Service – The following equation gives the value (in dollars) of oxygen as an ecosystem service per year , per capita. This equation is notated as f($$_{ES}$ O_2).

f($$_{ES}$ O_2) = [(1 oxygen ecosystem service / 3 ecosystem services) *

($40,340 yr^{-1} per capita for all ecosystem services)] -

($2000 yr^{-1} for manufactured oxygen)

= $11, 450 yr^{-1} per capita for oxygen ecosystem service

= **$10, 000 yr^{-1} per capita for oxygen ecosystem service**

Rationale:

1. For the straw-man calculation, "all ecosystem services" consist of only 1) gas exchange (oxygen and carbon dioxide), 2) water, and 3) waste decomposition (liquids and solids) so that each ecosystem service is worth 1/3 of the total. And because of the stoichiometric relationship between oxygen and carbon dioxide (see above), oxygen can count for both components of the gas exchange service.
2. The deduction of \$2000 yr^{-1} captures the opportunity cost of living off of manufactured oxygen provided by a health care provider at approximately \$150 mo^{-1}. Such a system delivers up to 4 L min^{-1} at a fixed-hose location and includes tanks for mobile access (Providence 2011).

Ecosystem Oxygen Production - The net primary production of oxygen by any individual green plant is the total oxygen produced by the plant (per unit of time) minus the oxygen consumed by plant respiration (per unit of time). Because of the stoichiometric relationships between oxygen and carbon dioxide in the process of photosynthesis, any plant that has a net accumulation of carbon during a year (growth) also has a net production of oxygen. The amount of oxygen produced can be calculated stoichiometrically from the amount of carbon sequestered (as CO_2) based on the atomic weights of oxygen and carbon:

$$\text{Net } O_2 \text{ release (kg yr}^{-1}) = \text{Net C sequestration (kg yr}^{-1}) \times (32 / 12)$$

In reality, net primary production of oxygen in any particular green plant is a function of numerous other functions including:

- species
- age and size
- health
- soil
- moisture regime
- temperature regime

Net Primary Production of Oxygen of Urban Trees - Nowak, Hoehn, and Crane (2007) investigated the net primary production of thousands of urban trees by evaluating trees contained in 3,222 circular plots across 16 US cities. Each circular plot measured 0.04 ha (0.1 acre). Standard, USDA Forest Service methods of data collection and evaluation were used. The results below are the results of the Nowak, Hoehn, and Crane (2007) study on urban trees.

Tree Dia. at Breast Hgt (1.37 m)	Size	**kg O_2 yr^{-1}**
1–3	sapling	**2.9**
9–12	small	**22.6**
18–21	medium	**45.6**
27–30	large	**91.1**
>30	giant	**110.3**

Monetary Value of Urban Trees as Ecosystem Service Providers of Gas Exchange --- The following general equation gives the value (in dollars) of an urban tree as an ecosystem service provider of gas exchange and is notated as f($_{ES}$ Urban Tree). The general equation is then applied to trees of varying sizes.

f($_{ES}$ Urban Tree)$_{size}$ = [\$10,000 yr^{-1} per capita] / [(400 kg O_2 yr^{-1} per capita) / (Urban Tree kg O_2 yr^{-1} $size^{-1}$)]

f($_{ES}$ Urban Tree)$_{small}$ = [\$10,000 yr^{-1} per capita] / [(400 kg O_2 yr^{-1} per capita) / (22.6 kg O_2 yr^{-1} $small^{-1}$)]
= \$565 per small tree
= **\$600 per small tree**

f($_{ES}$ Urban Tree)$_{medium}$ = [\$10,000 yr^{-1} per capita] / [(400 kg O_2 yr^{-1} per capita) / (45.6 kg O_2 yr^{-1} $medium^{-1}$)]
= \$1140 per medium tree
= **\$1000 per medium tree**

f($_{ES}$ Urban Tree)$_{large}$ = [\$10,000 yr^{-1} per capita] / [(400 kg O_2 yr^{-1} per capita) / (100 kg O_2 yr^{-1} $large^{-1}$)]
= \$ 2500 per large tree
= **\$2000 per large tree**

Rationale:

1. Ecosystem services can be provided by urban forests as well as by non-urban forests. In fact, some measure of ecosystem services are provided by any area where green plants are growing.
2. Once a quantity of an ecosystem service is defined (400 kg O_2 yr^{-1}in the straw-man case) and a monetary value is assigned to that ecosystem service (\$10,000 yr^{-1}in the straw-man case), then the dimensions of the portion of biosphere needed to produce the ecosystem service can be mapped and assigned monetary value. Obviously, there are density differences in the ability of various portions of the biosphere to produce ecosystem services (a hectare of spruce-fir woodland has higher ecosystem service density then a hectare of Sonoran desert). In the straw-man case, all of the ecosystem service for gas exchange (oxygen production) comes from urban trees and so trees themselves can be assigned a discrete monetary value.

Summary and Conclusions

The economic evaluation of resource amenities is an absolutely necessary requirement for bringing modern economic systems into modern reality. Currently, economic evaluations of resource amenities are secondary techniques because they are premised on human culture. This paper provides a first attempt at an economic evaluation of resource amenities based on a primary technique that is premised on biological constraints. A "straw-man" calculation is performed to show how such a primary technique would be applied. Based on the straw-man calculation, the value of urban trees as ecosystem service providers range in price from $600 for a small tree to $2000 for a large tree. Hopefully, primary techniques will be developed as another valid approach for the valuation of resource amenities and can then serve as a cross-check on secondary techniques.

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