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Ecological Footprint Budgeting: Environmental Analysis of the Generic American Car

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Environmental Analysis of the Generic American Car

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Abstract

This paper presents a method of environmental assessment that incorporates the strengths of ecological footprint and process based life cycle analysis. Like ecological footprint, product ecological footprint delineates between sustainable and unsustainable consumption. The ecological footprint of individual products allows consumers to budget their consumption within this limit. The resolution of product ecological footprint can be scaled, like life cycle analysis, to compare one feature, process, or product against another.

This study calculates the product ecological footprint of the generic American automobile using industry life cycle inventory, US statistical data, and data on global ecological capacity. It considers CO_2 emissions, mining impacts, and land directly occupied as the major contributors of land use. The conversion of these impact categories to hectares of ecological services was performed using a top down approach, based on global supply. The sources were chosen to produce a lower-bound estimate rather than the true ecological footprint.

Based on this study, the average car owner in the US expends at least 50% (0.8 hectares) of their ecological budget on driving alone. The footprint of a car is dominated fuel efficiency. The actual footprint may range from 30% to over 100% of one's ecological budget, corresponding to fuel efficiencies between 55 mpg and 12 mpg. The ecological footprint of the average automobile is more than 800 times the area it occupies physically.

The metric of land communicates environmental impact in an immediate and tangible manner. Land accurately represents the importance of ecological services over resources alone. It is one of few metrics that can compare dissimilar products and processes. Accordingly, product ecological footprint enables consumers to formulate and follow a personal ecological budget. The results of this study are designed to be meaningful to consumers and producers in hopes of provoking societal changes that will push industry towards sustainable design and manufacturing.

Introduction

The personal automobile use is not only harmful to the environment but also to global political relationships The rise of automobile use continues to outpace population growth. Environmental impact assessment techniques such as life cycle analysis are helping people think about the effects of their consumption, but results in terms of "tons equivalent CO_2 global warming potential" have no inherent meaning to consumers today. While life cycle analysis is useful for industry, there exists no adequate analog for consumers.

To meet this need, this paper proposes a new method of environmental impact assessment based on Wackernagle and Rees' ecological footprint analysis. The main concept of ecological footprint is that the tangible metric of land can represent the ecological capacity of the earth. Ecological footprint shows that the environmental load of our consumption now exceeds the limited environmental capacity of the earth at the cost of others. We must understand the ecological demand of the products and services we use in order to avoid overstepping and thereby compromising the regenerative capacity of our land.

Because its impact is hypothesized to be significant, a generic American sedan is evaluated in this paper using ecological footprint budgeting analysis. The results of this study are designed to be meaningful to the general public and applicable to other products and services, in the hopes of provoking the societal changes that will push industry in the direction of sustainable design and manufacturing.

2. Environmental Impact Assessment Background

The purpose of environmental impact analysis is to evaluate the sustainability of products, services and even lifestyles. The Bruntland Report of 1987 defines sustainability as "the ability of humanity to ensure that it meets the needs of the present without compromising the ability of future generations to meet their own needs."[1] Environmental impact assessment aims to enable us to make informed decisions for our collective benefit.

2.1. Life Cycle Analysis

Life Cycle Analysis (LCA) is the current standard system of assessing environmental impact, adopted by both industry and special interests. LCA is a way of assessing the total impact on the environment due to a product or service, such as a car or transportation from point A to point B. LCA measures impact through every phase of the life of the product or service, from material extraction, through use, to final disposal. The definition of Life Cycle Analysis from the International Organization for Standardization (ISO) 14000 family of international standards on Environmental Management is as follows.

> “A systematic tool for assessing the environmental impacts associated with a product or service system to:
>
> - build an inventory of inputs and outputs,
> - make a qualitative and quantitative evaluation of those inputs and outputs, and
> - to identify the most significant aspects of the system relative to the objectives of the study” [2]

Life cycle assessment is generally performed in two steps. First, an inventory of all potential environmental impact contributor flows must be recorded. Second, the contributor units must be converted to common units so that they can be quantified and compared.

2.1.1. Life Cycle Inventory

The first component of a lifecycle analysis is a life cycle inventory (LCI). An LCI is a list or comparison of all flows involved in each part of a product life cycle. A life cycle inventory can be built using a pictorial tool known as a process tree (Figure 1). Each box below represents a process, a part of the life cycle, each with its own input and output flows.

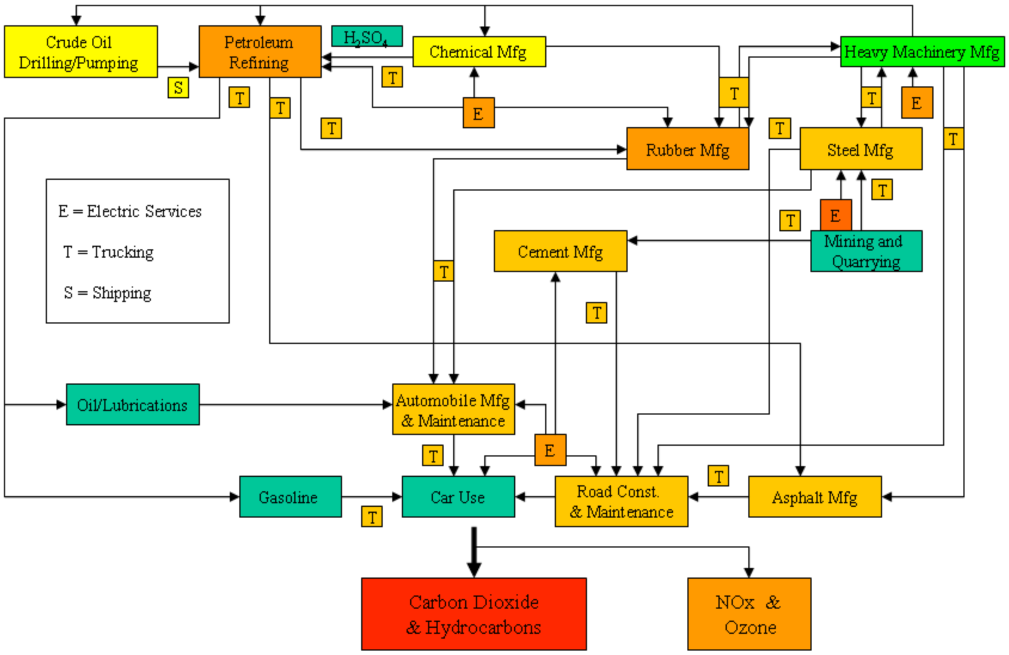

Figure 1: Process tree for car use, not including downstream processes

Commonly, flows contributing to environmental impact are quantified economically in terms of dollars or physically in terms of materials or energy consumption. Material flows may include emissions such as carbon dioxide, hydrocarbons, nitrogen oxides, and particulates.

With this information, producers can identify the processes in a product life most responsible for environmental or economic stresses. The contributor flows or processes with the greatest impacts can be targeted specifically in this way. For example, life cycle inventory shows that the energy expenditures from the use phase of a car far exceed those incurred in manufacturing, disposal, or elsewhere in the process tree. Therefore, it is much more meaningful to invest in improving energy efficiency in vehicle use rather than in manufacturing.

From a systems point of view, a LCI may also be very useful. If the outputs of one process, waste heat for example, may be utilized elsewhere, LCI will show this clearly. This facilitates the development of "closed loop" manufacturing systems, or systems that utilize all material wastes as inputs for other processes.

2.1.2. Life Cycle Impact Assessment

The next step of LCA, called Life Cycle Impact Assessment (LCIA), is to assign a value of environmental impact to each contributor flow in the inventory. This is necessary so that we can compare dissimilar flows in common units. There are currently many methods used, based on a product's contributions to global warming, acid rain, human toxicity, energy depletion, nitrification, ozone depletion, etcetera[3].

By analyzing LCIA, we can evaluate the aggregate environmental impacts of two product or service options. Cars made of fiberglass composite are lighter and therefore consume less gasoline during their lifetime than solid steel framed cars. However, LCA may show that composites complicate recycling and end-of-life processing enough to counteract the benefits of improved fuel economy[4]. Companies use LCA in this way to compare their product with that of their competitors. Common examples of such comparisons include paper versus Styrofoam cups, cloth versus disposable diapers, and paper versus plastic grocery bags[5].

However, lack of information and lack of consensus make a difficult task of assessing environmental impact. With different assumptions and varying levels of detail, it is possible for special interests to manipulate LCIA to their benefit. For example disposable razor manufacturers can make certain assumptions to make their product seem more environmentally benign than electric razors, and vice versa.

LCA empowers industry and consumers to make the more environmentally benign choice from available options. However, LCA fails to tell us if the ecological consumption of either option allow us to remain within sustainable limits.

2.2 Ecological Footprint

While LCA is useful to industry, Ecological Footprint (EF) is designed for the general public. EF is a tool used to assess how much land is required to sustain a particular lifestyle based on one's consumption of food, transportation, housing, and other goods and services compared to how much land is available for each person. Mathis Wackernagle and John Rees first developed this method of impact assessment, which they describe as an accounting framework capable of determining how much humans occupy of the earth's regenerative capacity[6]. Wackernagle writes that Ecological Footprint analysis is based on the five following assumptions.

> **"Ecological Footprint calculations are based on five assumptions:**
>
> 1. It is possible to keep track of most of the resources people consume and many of the wastes people generate. Much of that information can be found in existing official statistics.
> 2. Most of these resource and waste flows can be converted into the biologically productive area that is required to maintain these flows.
> 3. These different areas can be expressed in the same unit (hectares or acres) once they are scaled proportionally to their biomass productivity. In other words, each particular acre can be translated to an equivalent area of world-average land productivity.
> 4. Since these areas stand for mutually exclusive uses, and each standardized acre represents the same amount of biomass productivity, they can be added up to a total—a total representing humanity's demand.
> 5. This area for total human demand can be compared with nature's supply of ecological services, since it is also possible to assess the area on the planet that is biologically productive." [7]

The metric of land not only represents the area directly affected by our consumption but also the biological capacity of the land necessary to support our consumption. In this way, land based assessment enforces the importance of the earth's ecological services over its resources. Though many people worry about the depletion of natural resources, materials production is only one of the many services our environment provides for us. Others of equal importance include climate control, carbon cycling, air oxygenation, water purification, nitrogen cycling, solar energy harnessing, and biodiversity support.

Ecological footprint is meaningful because it is a measure of consumption of environmental services with respect to supply. The total productive land on earth represents the total supply of environmental services. Land is capable of providing a limited amount of services in a sustainable way. This limit can be exceeded at the cost of future service capabilities, as is typified by the reduced productivity of over-fished waters.

According to Redefining Progress, we are currently exceeding the regenerative ability of the earth to sustain us. In 1961, man's collective environmental load occupied 70% of the earth[8]. Because of rising standards of living and population growth, today we occupy 145% of the earth's regenerative ability[9].

Assuming each person has an equal right to enjoy those services, the land available for each person is the total amount of productive land in the world divided by the world population. By this measure, ecological footprint assessment boils environmental concerns down to a question of ethics. If one exceeds the use of their fair share of land, they are drawing upon the goods of another. Ecological footprint analysis outlines otherwise invisible limits on sustainable consumption.

However moved are consumers by the messages of ecological footprint, they cannot obtain concrete ways of improving their sustainability from this method. While LCA fails to report environmental impact in relation to sustainable limits, ecological footprint fails to demonstrate options for reducing ones impact.

3. Product Ecofootprint

Product Ecofootprint is a method of assessing the environmental impacts of products in a way that can be translated to ecological availability and in simple, non-obscure units. This technique makes use of the inventory and impact assessment concepts of life cycle assessment as well as the comparison to available ecological capacity that is the cornerstone of ecological footprint analysis.

Product ecofootprints are built on life cycle inventory in the same way as traditional LCA. However, it draws on the ideas behind Ecological Footprint analysis for the impact assessment step. The land required to sustain all the process flows for a product can therefore represent the product's total environmental impact. For each measure of process flow, there is a different method of conversion to the metric of land. Each method is individually tailored to best represent the actual amount of land necessary to sustain the contributor flow.

Like ecological footprint analysis, product ecofootprint measures the environmental loads of products not against each other but against the load that the environment can sustainably support. Since land represents ecological capacity, sustainable consumption is defined as what our land resources can support. Each person's fair share of land is found by dividing the amount of productive land in the world by the world population.

With the rise of globalization, it has been increasingly clear that a country can appear to have better environmental performance than it really does by importing goods and exporting wastes. Furthermore the productivity of our land hinges on its ecological inertia. The failure of Columbia University's Biosphere 2 project is an illustration of how ecosystems must exceed a certain bulk threshold in order to be self-sustaining. The entire earth must therefore be considered to understand our true impacts on the earth.

Unproductive land and water surface area were excluded from this study because this produces the most useful visual tool. Most people tend to value and visualize productive land over bodies of water, deserts, or land covered with ice. Moreover, carbon uptake data on productive land is much more reliable than that on any other area.

Product ecofootprint analysis shows first, that our world is environmentally constrained. Second, it shows the environmental demands a consumption choice may make on our limited services and therefore ways individuals can attempt to minimize their ecofootprint. While an Ecological Footprint is an assessment of a lifestyle, a Product Ecofootprint is the assessment of a particular part of one's lifestyle.

The results of this analysis show not the potential ramifications of our consumption but simply that our consumption in relation to availability is out of balance. In this way, they are immune to disputes over impact categories. For example, those who reject the idea of anthropogenic global warming may neglect the effects of carbon dioxide emissions. However, the amount of land required to absorb an amount of carbon emissions relative to land available is not subject to such debate.

4. Methodology and Assumptions

Among the biggest consumers of energy, and therefore sources of global warming gasses, is our ever-increasing need for transportation. The transportation sector is responsible for one third of total energy expenditures, or 27 Quadrillion BTUs a year in the US alone[10]. This being said, it is important that we understand the origins of the impact due to transportation so that we can best minimize stress on our environment.

As a demonstration of this impact assessment technique, I performed an analysis of the ecofootprint of a car based on the data in this section. All contributions to environmental load are converted to units of land utilized by one car over one year.

4.1. Life Cycle Inventory

The life cycle inventory of the standard car is based on a combination of sources. John Sullivan and other members of the Society of Automotive Engineers performed an LCI of a generic US sedan for vehicle characteristics outlined in Table 1.

Table 1: Vehicle characteristics[11]

Weight	1532 kg
Fuel	Gasoline
Average Fuel Efficiency	23 miles per gallon (city 20, highway 29)
Vehicle Life	120,000 miles

Though it is very detailed, the paper by Sullivan et al lacks important information on automobile use and fails to represent the cross section of cars on the road in the US. In order to more accurately portray the environmental load of the average car, I used data from the US Bureau of Transportation Statistics' *National Transportation Statistics 2002* report.

Table 2: US vehicle use characteristics

Vehicle Miles Per Year	11988 miles/year[12]
Vehicle Life	10 years
Number of Registered Cars	133.6 million (213.5 million vehicles total)[13]
Average New Car Cost	$23,480[14]

The cost of a new car can be used as an indicator of the environmental load due to car manufacturing (see Section 5.1.2.3). The annual ecological demands of a car can represent its manufacturing phase if this cost is amortized over the lifetime of the car. Since the manufacturing footprint of a car is not reflected by its resale prices, only prices of new cars were use in this study.

4.2. Life Cycle Impact Assessment

The next step of product ecofootprint analysis is to find how many hectares of land are required to support each LCI process flow. Because each contributor to environmental impact has a different relationship with land, each requires unique contributor to land conversion factors.

In many cases, I found the conversion factors by dividing the amount of land needed to produce that contributor flow by the total contributor amount. For example, the ecological footprint of a kilogram of iron ore can be approximated by dividing the total iron mining land in the US by the amount of iron ore produced. This may not be extremely precise but it can be more reliable than other estimates.

Alternately, this conversion factor can be found using a bottom up approach. The ecofootprint of iron ore can be extrapolated from the depth and concentration of iron ore in various US mines. The ecofootprint of one kilogram of iron ore is the surface area of the mine divided by the weight of the iron removed multiplied by the overburden factor.

Again any impacts the car accrues in non-use phases of the product life cycle are equally divided over its life span. In this case, the iron ore amount needed for the car per year is only one-tenth of the amount in the car at any one time. However, the land used for mining is rendered unproductive by the mining process for at least 10 years[15]. In order to measure the ecofootprint of iron ore per car per year, the contributor amount must be divided over the use phase and the land/contributor conversion factor must be multiplied by the duration of land impact.

Both cases are extremely simple and conservative. Likewise this study performs a simple and conservative study of the overall land impacts of an American car. These methods do not factor in the added land impacts of the disposal of mining overburden, manufacturing and use of mining machinery, production of toxic pollutants, reduced productivity of land used for mining, transportation costs, etcetera.

Specific calculations for conversion to land for carbon dioxide emissions and materials use are outlined in the data section.

4.3. Land Availability – World land

There is a wide spread of what can be considered the land available per person. The following table shows the span of available area divided by the population that it supports.

Table 3: Total Available Land and Available Land Per Person

Scope	Total Hectares	Hectares per Person
World Total Surface Area	51.0 billion ha	8.1 ha/person
World Productive Surface Area	10.7 – 1.25 billion ha	1.7 – 2.0 ha/person
World Total Land	13.0 – 15.1 billion ha	2.0 – 2.4 ha/person
World Productive Land	**8.15 – 9.41 billion ha**	**1.3 – 1.5 ha/person**
US Total Land	9.1 million ha	3.3 ha/person
US Productive Land	1.74 – 4.21 million ha	0.6-1.5 ha/person
Note: data chosen for use in analysis are in bold in this and following tables		

For the reasons explained in section 3.0, each person's fair share of land is an equal portion of the world productive land. Therefore, the sustainable ecofootprint of each person is 1.5 hectares or 3.7 acres.

The World Commission on Environment and Development conservatively suggests that 12 percent of the ecological capacity of the earth be reserved in order to protect the other 10 million species on earth. Since this number is still controversial, this study does not allocate any land for biodiversity.

However, this assumption does not imply that these other species are superfluous. Rather, other organisms, and the ecosystems they form, are responsible for providing the environmental services on which we depend. In order to maintain the ecological capabilities of our environment, each of us must share our land with other species.

5. Land Use Data

I found data from a variety of sources. However the data used for analysis where chosen because they are reliable, current and relatively non-extreme in value. This section discusses the contributors of environmental load in a car and their derivation. Table 4 is a summary of the land utilized by each contributor source.

Table 4: Car Land Use Contributors

Contributor Source	Contributor Amount	Contributor Unit	Land (ha) per unit contributor	Land (ha) per car
CO_2 Gasoline	5.13E+00	ton CO_2	5.935E-02	3.05E-01
Roads	1.05E-01	ha Land	1.000E+00	1.05E-01
CO_2 Petroleum Refining	1.28E+00	ton CO_2	5.935E-02	7.58E-02
CO_2 car manufacturing	1.12E+00	ton CO_2	5.935E-02	6.67E-02
Iron Mining	1.44E+03	kg Iron	1.714E-05	2.47E-02
CO_2 road building	2.45E-01	ton CO_2	5.935E-02	1.45E-02
Parking	1.44E-02	ha Land	1.000E+00	1.44E-02
CO_2 road maintenance	1.54E-01	ton CO_2	5.935E-02	9.13E-03
CO_2 car maintenance	6.15E-02	ton CO_2	5.935E-02	3.65E-03
Coal Mining	2.51E+03	kg Coal	4.900E-08	1.23E-04
			TOTAL	**6.18E-01**

5.1. CO2 Impacts

Each year every car emits 8.0 tons of carbon dioxide. These emissions are significant, occupying 77% of a generic American sedan ecofootprint. Modeling the land impacts of emissions requires not only information on how much is produced but also on how much is absorbed by a fixed amount of land over a fixed length of time.

5.1.1. Absorption

Carbon dioxide emissions are equated to land in this study using information on global carbon absorption. The seven studies I found report carbon absorption rates ranging from 6.9 to 44.1 tons of carbon dioxide per hectare per year because the scope of their studies vary greatly. There is no consensus on whether or not to include deserts, land covered with ice, land made up entirely of ice or other bodies of water.

A recent study from the MIT Joint Program on the Science and Policy of Global Change showed world terrestrial carbon absorption at 47.9 petagrams per year assuming terrestrial surface area of 130.3 million square kilometers[16]. The amount of carbon directly absorbed per unit of land is the product of these two figures.

Oceans are responsible for 19 to 21 percent of global carbon absorption and so this must be included in the calculation[17]. The amount of carbon absorbed per unit of land including the proportionate amount of water it represents is therefore 1.25 times more than that absorbed by land alone.

The molecular mass of carbon dioxide is 3.7 times greater than that of carbon alone. Therefore, 3.7 tons of carbon dioxide is absorbed for every ton of carbon calculated above.

Table 5: Derived carbon dioxide absorption rates

Source	Tons CO2 per hectare per year
BIOME-BGC[18]	44.14
MRS[19]	20.50
Atjay[20]	19.37
Hart[21]	18.70
Xiao[22]	**17.97**
Melillo[23]	16.77
Frey[24]	6.94

Using terrestrial absorption rates from Xiao, the amount of land required to support the absorption of each kg of carbon dioxide is 55.6 hectares per kilogram of carbon dioxide.

5.1.2. Production

5.1.2.1.Gasoline

A majority of the carbon dioxide emitted by an automobile occurs in its use phase as a result of gasoline combustion. Gasoline is a hydrocarbon with the number of carbons varying from 4 to 20. Assuming gasoline is composed solely of octane, we can use the following chemical equation.

Equation 1: Complete Combustion of Octane

$$2\ C_8H_{18} + 25\ O_2 = 16\ CO_2 + 18\ H_20$$

Complete combustion of 1 kilogram of gasoline results in the emission of 3.17 kilograms of CO_2. One gallon of gasoline has a mass of 2.85 kilograms. Assuming the car has a fuel economy of 23 miles per gallon, 393 grams of carbon dioxide are produced every mile driven. This is consistent with data from John DeCicco's *A Method for Green Rating of Automobiles* for the Journal of Industrial Ecology that finds 410 grams of carbon dioxide emitted per mile driven[25]. Given the average car logs 11,988 miles every year, there is 4.71 tons of carbon dioxide emitted by each car every year.

However, this assumes complete combustion of a relatively light hydrocarbon at perfect efficiency. Sullivan's study is perhaps more realistic. He found that 51.3 tons of carbon dioxide is emitted over the life of an automobile in the use phase[26]. If this amount is distributed evenly over the 10 years of the vehicle life, each car emits 5.13 tons of carbon dioxide every year.

The website www.fueleconomy.gov employs a fuel cycle model developed by Argonne National Laboratory called Greenhouse Gases, Regulated Emissions and Energy

Use in Transportation (GREET)[27]. Sullivan's paper is based on a generic American sedan, which is based on the averaged characteristics of the Chevrolet Lumina, the Dodge Intrepid, and the Ford Taurus. The global warming gas emissions predicted for these cars according to www.fueleconomy.gov are respectively 8.3 tons, 7.9 tons and 8.8 tons of carbon dioxide equivalent[28]. Carbon dioxide only makes up 85% of all emitted global warming gas emissions according to Carnegie Mellon's Economic Input Output Life Cycle Analysis (EIOLCA) calculator, and so the average carbon dioxide emissions of these cars is 7.1 tons every year[29].

Though this model is the most detailed and likely the most accurate, subsequent calculations make use of Sullivan's numbers for carbon dioxide emissions to yield more conservative and consistent results.

Table 6: Use phase carbon dioxide emissions from various sources

Source	Tons CO2 per car per year
Complete combustion of octane	4.71
Sullivan	5.13
GREET	**7.10**

5.1.2.2.Gasoline Production

A number of calculations of carbon dioxide emissions due to petroleum refining show that its environmental load is significant. In all cases, I ignored petroleum use in all life stages of the car except for the use phase.

I used Carnegie Mellon's Economic Input Output LCA calculator to derive annual carbon emissions based on the cost of gasoline used per car per year. Assuming a car is driven 11988 miles per year with an economy of 23 miles per gallon at 2002 gasoline prices, EIOLCA finds that there is 1.00 ton of carbon dioxide produced per car per year due to petroleum refining[30]. However, the process of refining petroleum is not completely representative of the environmental impacts of gasoline production.

In order to find a better estimate of carbon dioxide emissions due to gasoline production, I referenced two recent papers on energy and transportation. Both MIT's *On The Road in 2020* report and DeCicco's *A Method for Green Rating of Automobiles* paper provide data on environmental impact from the fuel supply cycle as a proportion of the emissions of that from the use phase.

On the Road finds that for every 10.0-mega joules of energy consumed in the use phase, 2.1-mega joules were used to refine the gasoline[31]. Assuming a direct relationship between energy use and carbon dioxide emissions, 1.08 tons of carbon dioxide is emitted in the fuel cycle of each car every year.

A Method of Green Rating of Automobiles reports that for every mile driven, gasoline combustion produces 410 grams of carbon dioxide while gasoline production produces 122.5 grams of carbon dioxide[32]. Given the same car use per year as the previous two calculations, I found that gasoline production is responsible for 1.53 tons of carbon dioxide for every car every year. This analysis is useful but does not give control over the fuel efficiency of the car at question.

DeCicco also provided information on carbon dioxide emissions per gallon of gasoline. If each gallon requires the emissions of 2.45 kilograms of carbon dioxide and every car has a fuel economy of 23 miles per gallon, then the fuel cycle for every car is responsible for 1.28 tons of carbon dioxide per year[33]. This was the figure used in my final analysis since it is the most directly related and thorough study.

Table 7: Gasoline production carbon dioxide emissions from various sources

Source	Tons CO2 per car per year
Economic Input Output LCA	1.00
Weiss et al	1.08
DeCicco per gallon gasoline	**1.27**
DeCicco per use phase CO2	1.53

5.1.2.3.Car Manufacturing

Carnegie Mellon's Economic Input Output LCA was used again to assess the carbon dioxide emissions from car manufacturing in a fashion similar to that which was used to analyze gasoline production. Given the average cost of a car (Table 2) is spread equally along its 10-year life, the manufacturing costs of a car represent to 1.96 tons of embodied carbon dioxide emissions per year according to EIOLCA[34]. It is important to note that the costs evaluated do not average in the sale prices of used vehicles. This is because the manufacturing costs of a car are reflected in the initial sale price and not in subsequent resale prices.

Sullivan reported 7.00 tons of carbon dioxide is emitted in manufacturing a car. The emissions per year are therefore only 0.70 tons. This figure is 2.8 times smaller than that shown through EIOLCA.

To reconcile these two numbers, I looked to DeCicco's paper for data on embodied carbon dioxide emission in vehicle bodies. He found that each mile driven represents 93.7 grams of carbon dioxide are embodied in the vehicle. At average vehicle miles, this means that the manufacturing of each car is responsible for 1.12 tons of carbon dioxide every year.

Deluchi's *Emissions of Greenhouse Gases from the Use of Transporation Fuels and Electricity* found that 55.9 grams of carbon dioxide are emitted per mile for a car weighing 992 kilograms[35]. Assuming a linear relationship between the mass of the car and carbon dioxide emissions, this means 86.3 grams of carbon dioxide per mile for our generic vehicle. At 11,988 miles per year, Deluchi's data finds that 1.03 tons of carbon dioxide is emitted for gasoline production for each car every year.

Table 8: Car manufacturing carbon dioxide emissions from various sources

Source	Tons CO2 per car per year
Sullivan	0.70
Deluchi	1.03
DeCicco	**1.12**
Economic Input Output LCA	1.96

5.1.2.4.Road Building and Maintenance

Every year, \$33.6 billion are spent for road building and \$23.1 billion for road maintenance in the United States. Carnegie Mellon's Economic Input Output calculator is capable of converting spending to emissions in these two categories. If our annual expenditures on road building are distributed evenly between all registered cars in the US, 245 kilograms of carbon dioxide are emitted per car per year. Likewise, 154 kilograms of carbon dioxide are emitted due to road maintenance per car per year in the US.

5.2. Direct Land Impacts

Road infrastructure differs from other categories in that there is a direct conversion from contribution to land. Janet Larsen of the Earth Policy Institute performed a study of the amount of land dedicated to automobile use in the US by collecting information on the total lengths and average widths of 12 major road types in the US. She found that there are 14.0 million hectares of land used for roads in the US[36].

I verified her findings with data from the Bureau of Transportation Statistics. There are 3.96 million miles of roads in the United States[37]. The minimum width allowed for two lane roads in Hong Kong is 39.6m[38]. I assumed that all roads in the US contain only one lane that is 20m wide. To say the least, this is a very conservative estimate of land covered by roads. This calculation approximated 12.6 million hectares of road-land, supporting Larsen's findings.

On top of land devoted to roads, there is a non-negligible amount in parking, gas stations, garages, and dealerships. Larsen found that there are 1.9 million hectares of parking in the US or more than 3 parking spots per car[39]. However, information on the other contributors is not readily available and difficult to estimate with much certainty.

Assuming all 134 million registered passenger cars in the US use roads equally[40], there are 0.1047 hectares of road per car. Likewise, there are 0.014 hectares of parking for each car in the US. The direct land use of the average American car is therefore 0.1191 hectares every year.

5.3. Mining

Sullivan conducted an LCI of the raw materials use of the generic vehicle. Outside of petroleum products, the greatest inflows were coal, iron and water. Iron and coal are discussed in this section.

Mining has an added dimension of time to consider. We saw before in the manufacturing section that pre use phase environmental demands must be amortized over the life of the product in order to approximate its annual load. Mining is different from the previous impact categories because the impacts incurred over one year last for many years. When iron is extracted from the ground, the land is devastated. It will take on the order of 10 years before the land can be productive in any way[41].

5.3.1. Iron

As mentioned in section 4.2, the amount of land required to mine a kilogram of iron can be estimated by dividing the amount of land used for iron mining in the US by the quantity of iron produced. Since the US Bureau of Mines was disbanded, however, the amount of land used to mine each commodity is very hard to find.

In 1974, James Paone et al reported for the US Bureau of Mines the amount of land utilized for mining of various commodities including iron in 1974. However, American iron resources are less plentiful than they were 30 years ago and so Paone's findings are now out of date.

If we assume the size of iron ore mines remains constant, the number of mines in the US can represent the land covered by mines in the US. I therefore estimated the land covered by each iron ore mine by linearly extrapolating the number of iron mines in the US as according to the National Mining Association back to 1971. If we also assume the ratio of iron ore mining land to total metal mining land is 21% today as it was in 1971[42], there were approximately 500 hectares of iron ore mines in the US in 2001.

Since there were 29,300 tons of iron ore metal content mined in 2001[43], the ecfootprint of each kilogram of iron ore metal content is 17.1×10^{-5} hectares. However, the ecofootprint of metal in a car is the ecofootprint of each ton of metal in the car, amortized over the car life and multiplied over the length of time before the mined land can be productive again. Since both of these figures have been estimated at ten years, there is no net change.

I am guessing that this is a very conservative estimate since mines today must remove more material to recover the same amount of metal content as 30 years ago. Also, even reclaimed mining land is severely compromised in its productivity as land can be deemed reclaimed by the mining industry after the topography is leveled, and dirt and grass are laid on top. Because of residual contamination, this land is generally considered undesirable.

5.3.2. Coal

I performed the same analysis for coal mining land as I did for iron mining land. Using extrapolated aggregate data, I found 6.52 x 10^{-8} hectares of land are required to mine each kilogram of coal.

In the case of coal, however, I found previous work on the ecofootprint of coal mining in Sibylle Frey's *Environmental Assessment of Electronic Products using LCA and Ecological Footprint*. According to Frey, 1.80 x 10^{-8} hectares of land are required to mine every kilogram of coal[44] plus 3.10 x 10^{-8} hectares of land required for coal subsidence[45]. Her finding of 4.90 x 10^{-10} hectares per kilogram of coal supports my estimate.

Sullivan found that a car uses 2.509 tons of coal throughout its life[46]. Therefore coal extraction for a car requires 1.23 x 10^{-4} hectares of land per year as calculated by Frey.

5.4. Water

According to Sullivan, the generic car uses 76,959 liters of water over its life. To equate this ecological demand to the unit of land, I found that the average rainfall worldwide is 78 centimeters per year[47]. Therefore 9.9 x 10^{-2} hectares of land are needed to capture and filter water for each year of the car life.

Please note that this does not consider the much greater biological capacity required to filter wastewater from the car. It is unknown how much land and time is required to break down effluents in post-industrial and post-consumer water.

However, land that captures and filters water can also absorb carbon dioxide. Water and carbon dioxide represent a class of environmental impact contributors: those that are not exclusive in their land use. Others may include sulfur dioxide emissions, fossil fuel production, or mineral concentration. Of these land uses, only the largest land of uses should be added to the total car ecofootprint.

6. Results

Given that each global citizen has 1.5 hectares worth of biological capacity available to him or her, each person who owns and uses a car as the average American does expends 41% of their ecofootprint for their car alone (Figure 2). This is equivalent to 0.6 hectares or 1.5 acres of productive land every year. The ecofootprint of a car is consequently over 800 times greater than its physical footprint.

The total product ecofootprint of all sedans in America (319,000 square miles) would cover the entire state of Texas (268,600 square miles)[48]. If the rest of the world used cars like Americans do, the ecological footprint of cars would be more than double the land area of the United States.

Figure 2: Utilization of 1.5 hectares of available land by car use

Of the car ecofootprint, the impact of carbon dioxide is significant. The 8.0 tons of carbon dioxide emitted every year require 0.47 hectares or 1.17 acres of productive land. The land occupied by this contributor group will continue to grow as the atmosphere becomes more saturated with carbon dioxide and carbon uptake rates fall.

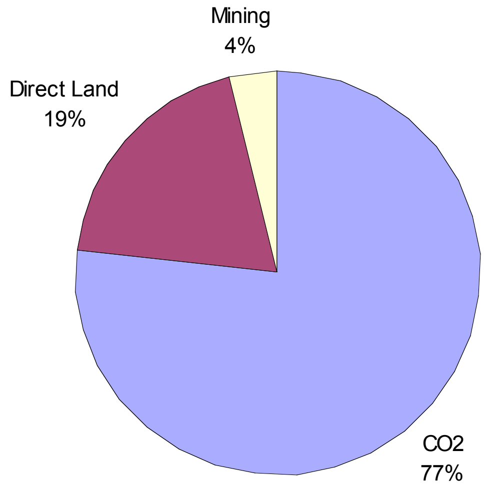

Figure 3: Utilization of car ecofootprint by contributor group

Furthermore, population growth will affect the relative use to availability of environmental capacity. By the year 2050 the US Census Bureau projects the world population to be 9.1 billion[49]. Assuming the amount of productive land on earth does not decline, there will only be 1.0 hectares or 2.47 acres of land available for each person.

7. Discussion

7.1. Sources of Error

Lack of data is the main source of error in both the LCI and the LCIA components of this study. Because environmental impact assessment is still a relatively new field, what little information exists is not always agreed upon. As a result, some parts of this study are based on data extrapolated and interpolated from the current body of knowledge. The results found here most likely underestimate the true ecofootprint of a car, as I have been conservative in both the inventory and the impact assessment steps.

7.1.1. Life Cycle Inventory

There is both lack of detail and lack of breadth in available information. For example Sullivan et al only assessed 644 parts out of 20,000 for their LCA of a generic vehicle. This study was a first approximation of primary contributors to environmental load. Unknown lower tier contributors such as gasoline transportation, mining machinery, and car retail were ignored. Similarly, consequences such as acidification, balances of other global warming gases, eutrophication, human health effects could not be assessed at all because they are not understood well enough.

Even in the amount of carbon dioxide emitted per mile driven, there is a great deal of variation. Estimates of use phase carbon dioxide emissions range from 4.7 to 7.1 tons given the same vehicle and vehicle use, which would have meant use of up to 2% less or 6% more of one's 1.5 hectares of land.

Furthermore, Sullivan's study is not representative of all vehicles on the road. Does not consider older cars and other vehicle types on the road that are much less efficient. This study did not consider any of the 7.9 million minivans, SUVs and trucks in the US[50]. Instead they assume a new, relatively light and inexpensive sedan.

Many basic assumptions of a generic sedan vary from source to source. In *A Method of Green Rating of Automobiles,* DeCicco and Thomas used a car weighing 1,674 kilograms (rather than 1532 kilograms from Sullivan's paper) and with a fuel economy of 20.0 miles per gallon (rather than 23.0 miles per gallon). Meanwhile, the average fuel economy of vehicles on the road in the US is closer to 22 miles per gallon.

7.1.2. Life Cycle Impact Assessment

As with the LCI, some numbers were approximated from aggregate data. For example, the amount of land currently used for iron ore and coal mining were based on trends over the last 30 years. Even the studies I referenced are guilty of this. Rates of carbon absorption are generally estimated from the net primary productivities of sample regions representing biomes, and the land area of various biomes.

Nor are there commonly accepted figures for the relative amounts of carbon absorbed by bodies of water and land, the impact of roads on surrounding land or the duration of time before mined land can be considered productive again.

Furthermore, economic input output LCA is sensitive to fluctuating prices. For example, the land utilized for fuel cycle carbon emissions could have been dramatically different given gasoline prices from a year before or a year after 2002.

7.2. Further work

This study is by no means comprehensive. It is a first approximation of the ecofootprint of a car based on data available today. Future studies of product ecofootprints may include more details. For a car, this may include analysis of land used for materials disposal, electronics manufacturing, filtration of wastewater, and other infrastructure. It would also be interesting to include land credits for ecological services a product may provide. For example the land equivalent of recycled car parts or water filtered in a manufacturing plant may be credited to the ecofootprint of a car.

Another approach for the LCIA would be to take the view of deep ecologists. A deep ecologist would study the geological activity of the earth to find out how much biological capacity and how much time is required to consolidate diffuse iron into useful concentrations. Petroleum, iron ore or coal production may be assessed based on the geological activity required to concentrate or form them instead of how much land is required to extract them.

The product ecofootprint assessment technique could be extended one step further. The economic valuation of land needed to support a car may be much more significant to many people than the value of the land itself. Such a study may indicate the true economic costs of a car.

It would be very interesting to compare a public pole of relative valuations of goods and service to their actual expenditures for each. In other words, how much are people willing to budget of their ecological capacity compared to how much they expend on goods and services, as broad as shelter, food, transportation, leisure activities, education and communication or as focused as air conditioning, handheld electronics, air travel, and packaged foods. This study shows that automobile use can take up 41% of ones available ecological capacity yet I doubt many people would value even transportation in general so highly.

8. Conclusion

The purpose of this study is not only to demonstrate the valuation of consumption against our environment's capacity for it, but to also show the specific consumption habits that dominate in terms of ecological weight. This study suggests that personal automobile use is a big consumer of ecological capacity. A compilation of all the products and services we use may give us both an understanding of how sustainable we are and ways in which we can improve.

Product ecofootprint better equips consumers and producers alike to make educated consumption choices. Product ecofootprint can show how our use and availability of ecological services may be out of balance. It is especially interesting as a way of communicating the implications of our consumption without the need for speculating long tern ecological responses. I hope that the results found using this analysis will bring "not in my backyard" considerations into play before environmental problems arrive physically.

Like ecological footprint, product ecofootprint make consumption an ethical issue. Consuming more than one's available ecological capacity means that someone in another place or time must do with less. In this way, product ecofootprint brings problems of excessive environmental load to the public in a manner that is both easy to understand and immediate. Only this can bring lasting and meaningful changes in our relationship with our environment.

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Appendix A: Life Cycle Inventory

Table 9 is from Sullivan's *Life Cycle Inventory of a Generic U.S. Family Sedan.* Only the raw material use of coal, iron and water were analyzed in this study because they are the materials used in the greatest quantity. The values below for natural gas and oil use were omitted to avoid double counting flows that may have been included in the carbon emissions from manufacturing.

Table 9: LCI of the Generic Vehicle (Raw Material Use)[51]

Inflow	Units	Generic Vehicle	Material Production	Manufacturing	Operation	Maintenance & Repair	End of Life
Bauxite	Kg	32	32	0.0026	0	0.021	0
Bauxite Rich Soil	Kg	222	222	0	0	0	0
Chromium	Kg	0.91	0.91	0.91	0	0	0
Coal	**Kg**	**2,509**	1,033	618	748	100	11
Copper	Kg	23	23	0	0	0	0
Ilmenite	Kg	0.97	0.32	0.65	0	9.9×10^{-5}	0
Iron	**Kg**	**1,443**	1,440	0.38	0	3.0	0.045
Lead	Kg	33	13	0.26	0	0.76	0
Limestone	Kg	485	199	95	142	21	2
Manganese	Kg	24	23	0	0	0.76	0
Natural Gas	Kg	1,810	491	216	1,027	73	2.2
Oil	Kg	16,486	631	87	15.562	171	35
Olivine	Kg	8.3	8.3	0	0	0.0032	0
Perlite	Kg	2.4	2.3	0.056	0	0	0
Platinum	Kg	0.0015	0.0015	0	0	0	0
Pyrite	Kg	13	13	0	0	4.3×10^{-5}	0
Rhodium	Kg	2.9×10^{-4}	2.9×10^{-4}	0	0	0	0
Sand	Kg	179	140	0	0	12	27
Sulfur	Kg	0.1	0.08	0.022	0	4.0×10^{-5}	0
Tin	Kg	0.48	0.067	0.41	0	0	0
Tungsten	Kg	0.012	0.011	0	0	6.8×10^{-4}	0
Uranium	Kg	0.039	0.01	0.0089	0.018	0.0019	2.5×10^{-4}
Zinc	Kg	22	22	0	0	4.3×10^{-4}	0
Cullet	Kg	0.013	0	0.013	0	0	0
Iron Scrap	Kg	243	200	0.05	0	43	0
Natural Rubber	Kg	25	8.8	0	0	16	0
Alloying Additives	Kg	4.0	4.0	0	0	0	0
Iron Casting Alloys	Kg	12	12	0	0	0	0
Unspecified	Kg	17	7.4	9.2	0	0.32	0
Steel Scrap	Kg	474	428	0	0	46	0
Water	**Liter**	**76,959**	59,672	9,818	2,007	5,459	4.0

Table 10 is also from Sullivan's *Life Cycle Inventory of a Generic U.S. Family Sedan.* Only carbon dioxide emissions were used for analysis in this paper.

Table 10: LCI of the Generic Vehicle (Outflows)[52]

Outflow	Units	Generic Vehicle	Material Production	Manufacturing	Operation	Maintenance & Repair	End of Life
Carbon Dioxide	**Kg**	59,092.2	4,439.85	2,562.16	**51,331.4**	615.481	143.273
Carbon Monoxide	Kg	1,942.23	63.813	5.914	1.832	39.088	0.683
Hydrocarbons except methane	Kg	256.64	12.627	7.349	234.520	1.974	170
Hydrogen Chloride	Gram	725	278	10402	402	29	5.7
Hydrogen Fluoride	Gram	113	59	1.1	50	2.0	0.7
Lead	Gram	115	50	1.2	1.1	63	0.015
Methane	Gram	65,806	11,773	5,534	44,500	3,854	144
Nitrogen Oxides	Gram	254,193	12,871	8,295	229,465	2,755	806
Particulates	Gram	53,526	26,470	8,235	16,525	2,050	247
Sulfur Oxides	Gram	133,326	30,491	14,917	83,180	4,424	315
Ammonia	Gram	2,354	116	17	2,208	12	1.9
Dissolved Matter	Gram	7,686	4,527	1,118	982	1,041	17
Heavy Metals	Gram	39	29	7.5	0	3.1	0.0013
Oils	Gram	7.611	130	516	6,918	39	7.4
Other Organics	Gram	80	77	0.43	0	2.5	2.2 x 10^{-4}
Phosphates	Gram	15	7.2	7.8	0	0.42	1.6 x 10^{-5}
Suspended Matter	Gram	74,321	2,779	2,450	68,522	512	58
Waste (municipal and industrial	Kg	415	22	56	8.0 x 10^{-5}	41	296
Waste (total)	Kg	4,213	2,440	386	783	277	326

Appendix B: Life Cycle Impact Assessment

Contributor to land conversion factors where calculated using the following equations and methods.

Carbon Absorption

Because there are no commonly accepted values for rates of carbon absorption per hectare of land, they were approximated using Equations 2-4.

Equation 2: Amount of Carbon Dioxide is estimated as World Absorption divided by World Land.

$$\frac{CarbonDioxideAbsorption}{UnitOfLand} = \frac{WorldCarbonDioxideAbsorption}{WorldLand}$$

Equation 3: More Carbon Dioxide Weight is absorbed per Molecule than Carbon Molecules Weight.

$$WorldCarbonDioxideAbsorption = WorldCarbonAbsorption \times \frac{MolecularMassCarbonDioxide}{MolecularMassCarbon}$$

Equation 4: Carbon Absorption of the Oceans are Included

$$WorldCarbonAbsorption = WorldTerrestrialCarbonAbsorption \times (1 + \frac{PercentOceanCarbonAbsorption}{PercentWorldTerrestrialCarbonAbsorption})$$

Roads

Every year, the US spends $33.6 billion building new roads. Carnegie Mellon's Economic Input Output LCA was used to equate expenditure to tons of carbon dioxide emitted.

Table 11: New highways, bridges, and other horizontal construction per million dollars.[53]

Sector	GWP MTCO2E	CO2 MTCO2E	CH4 MTCO2E	N2O MTCO2E	CFCs MTCO2E
Total for all sectors	1076.697405	972.366550	102.259481	0.685069	1.386305
Asphalt paving mixtures and blocks	351.840492	314.684203	37.087659	0.068630	0.000000
Electric services (utilities)	231.449480	207.105507	24.297880	0.046093	0.000000
Trucking and courier services, except air	102.658880	92.277479	10.205063	0.176338	0.000000
Cement, hydraulic	41.912186	38.204085	3.686860	0.021241	0.000000
Blast furnaces and steel mills	38.552014	35.745898	2.789066	0.017050	0.000000
Petroleum refining	30.256748	29.004455	1.164492	0.017256	0.070546
New highways, bridges, and other horizontal construction	27.346831	25.551268	1.753332	0.042231	0.000000
Ready-mixed concrete	24.061455	21.488951	2.540792	0.031713	0.000000
Water transportation	22.695094	21.071154	1.604964	0.018976	0.000000
Concrete products, except block and brick	16.235254	14.381219	1.828045	0.025990	0.000000

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The US also spends $23.1 billion on road maintenance annually.

Table 12: Maintenance and repair of highways & streets per million dollars. [54]

Sector	GWP MTCO2E	CO2 MTCO2E	CH4 MTCO2E	N2O MTCO2E	CFCs MTCO2E
Total for all sectors	985.372843	890.164165	93.285463	0.591485	1.331730
Asphalt paving mixtures and blocks	386.611035	345.782786	40.752837	0.075412	0.000000
Electric services (utilities)	204.471106	182.964732	21.465654	0.040720	0.000000
Trucking and courier services, except air	84.582249	76.028851	8.408110	0.145288	0.000000
Maintenance and repair of highways & streets	39.845962	37.229718	2.554710	0.061534	0.000000
Petroleum refining	29.584132	28.359678	1.138605	0.016872	0.068978
Blast furnaces and steel mills	23.643162	21.922229	1.710477	0.010456	0.000000
Dimension, crushed and broken stone	23.082868	21.434987	1.632793	0.015087	0.000000
Water transportation	20.756487	19.271263	1.467869	0.017355	0.000000
Industrial inorganic and organic chemicals	15.092600	13.332746	0.819810	0.007736	0.932308
Asphalt felts and coatings	12.269515	11.445281	0.811448	0.012785	0.000000

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Mining

The numbers of metal mines in the US over the last 20 years are shown in Figure 4. Assuming a linear relationship between the number of metal mines in the US and area of iron ore mines, Equations 5-8 where used to find the area utilized for iron mining decreased from 14,700 hectares in 1971 to 2,400 hectares in 2001.

Equation 5: Land Intensity of Iron Mining is Approximated from Iron Production and Land Use.

$$\frac{IronYeild}{UnitofLand} = \frac{IronYeild2001}{IronMiningLand2001}$$

Equation 6: Assuming Iron Mining Utilizes the Same Percentage of Metal Mining Land as in 1971.

$$IronMiningLand2001 = MetalMiningLand2001 \times \frac{IronMiningLand1971}{MetalMiningLand1971}$$

Equation 7: Assuming a Linear Relationship Between Number of Mines and Amount of Land.

$$MetalMiningLand2001 = \frac{MetalMines2001}{MetalMines1971} \times MetalMiningLand1971$$

Equation 8: Linear Extrapolation of Number of Metal Mines (Figure 4).

$$MetalMines1971 = -37.393 \times year + 74923$$

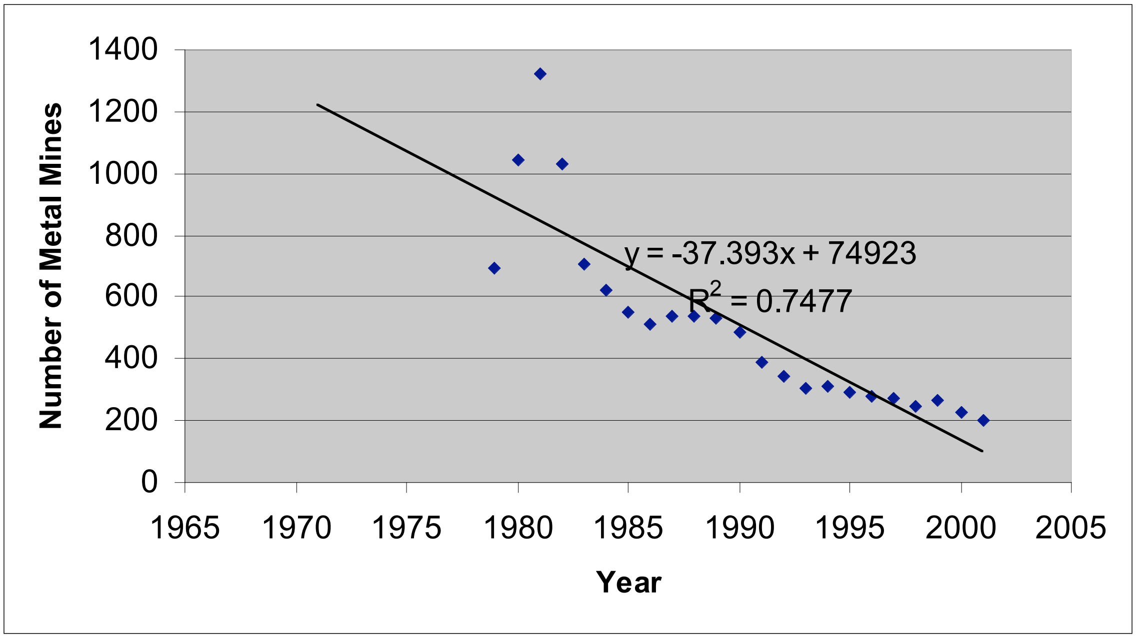

Figure 4: Number of US Metal Mines 1971-2001[55]

Coal

The land intensity of coal was found in a similar manner. However, this calculation was used only to support the findings of Frey (2000).

Equation 9: Land Intensity of Coal Mining is Approximated from Coal Production and Land Use.

$$\frac{CoalYeild}{UnitofLand} = \frac{CoalYeild2001}{CoalMiningLand2001}$$

Equation 10: Assuming a Linear Relationship Between Number of Mines and Amount of Land.

$$CoalMiningLand2001 = \frac{CoalMines2001}{CoalMines1971} \times CoalMiningLand1971$$

Equation 11: Linear Extrapolation of Number of Coal Mines (Figure 5).

$$CoalMines1971 = -198.03 \times year + 397600$$

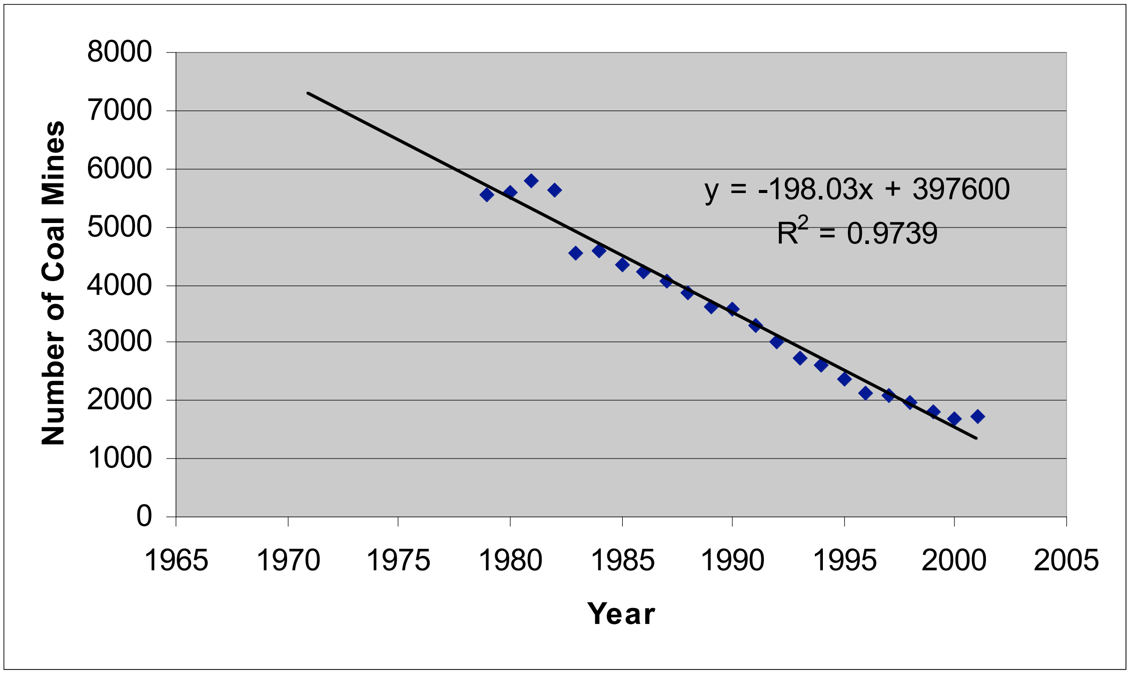

Figure 5: Number of US Coal Mines 1971-2001[56]

Water

The average world rainfall is 78cm[57]. If our land is capable of filtering all the rainwater that falls on it, the amount of rainwater filtered per unit of land can be calculated with Equations 12-14.

Equation 12: Land Intensity of Water Filtration.

$$\frac{RainwaterFiltration}{UnitofLand} = 78cm$$

Equation 13: Conversion to liters per hectare.

$$78cm = \frac{78cm \times 1cm^2}{1cm^2} \times \frac{1\times = 78 \times 10^4 L/h10^{-3} L}{1cm^3} \times \frac{1cm^2}{1 \times 10^{-8} ha} = 78 \times 10^4 L/h$$

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