Watch Your Step: Understanding the Impact of Your Personal Consumption on the Environment

by
Philip Camill
Department of Biology
Carleton College

Part I. Future Imperfect?

Imagine you could see into the future and watch the next 100 years unfold. Let's say that human populations, resource consumption, and waste continue to grow according to a business-as-usual scenario with few changes in policy or lifestyles to curb these trends. Would you notice a point when Earth is no longer able to sustain human population growth, resource consumption, and pollution? Have we already reached this point? How could you tell? What does it take to sustain life on Earth? The issue of sustainability is a challenging one, and the long-term survival of life as we know it may depend on how we define sustainability as well as the policies and lifestyle changes necessary to achieve it (Brundtland 1987).

Understanding how the Earth system sustains human life is a fascinating problem. Interestingly, space travel provided an early impetus for creating artificial life-support systems based on ecological principles similar to those of Earth's biosphere (Corey and Wheeler 1992, Galston 1992, Schwartzkopf 1992). The goal was to develop a self-sustaining biosphere in miniature that could extend the duration of space flights or allow humans to colonize another planet like Mars. In 1984, a company called Space Biospheres Ventures began the most ambitious example of this kind of research—a project called **Biosphere 2**—to replicate a self-sustaining biosphere like Earth's (a.k.a. Biosphere 1).

Columbia University Biosphere 2 Center has become an important experiment for understanding the life-support functions of the biosphere. Simply put, do we know enough about how the Earth's biosphere sustains human life to be able to replicate it or preserve it?

Fig. 1.
Biosphere 2 Lab

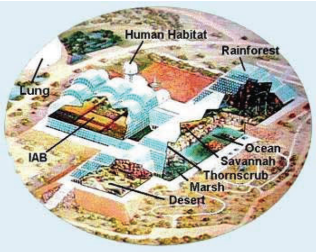

Fig. 2. Ecosystems in Biosphere 2 Lab

Fig. 3. Picture of the ocean ecosystem

All images of Biosphere 2 are the property of Columbia University Biosphere 2 Center and are used with permission.

Between 1984 and 1991, Columbia University Biosphere 2 Center was built in Oracle, Arizona, at a cost of over \$200 million (Nelson et al. 1993, Cohen and Tilman 1996) (see Fig. 1). The structure was not just a building where people could attempt to live sustainably—it was much bolder. Biosphere 2 was a giant glass chamber sealed off from the atmosphere that contained living ecosystems including a tropical rainforest, ocean, savannah, desert, marsh, and agricultural landscape (see Figs. 2 and 3). It enclosed 13,000m^2 of land and a total volume of 204,000m^3 (Cohen and Tilman 1996).

The original test of Biosphere 2 attempted to determine if these ecosystems could support the lives of eight people in perpetuity. Their only source of food was what they could grow in the agricultural sector. Their only source of oxygen was from plants and algae in the terrestrial and oceanic ecosystems. In 1991, the eight researchers were sealed in Biosphere 2, and the world watched.

In this case study, you will examine the issue of sustainability of humans on Earth using the concept of the "ecological footprint" (Wackernagel and Rees 1996). This is a powerful method for understanding sustainability and how to quantify it. As we will see, Biosphere 2 provides a good example of the ecological footprint concept because it represents a specific amount of land area (footprint size) and land use types thought sufficient to sustain the lives of eight people. We will see the outcome of the Biosphere 2 experiment at the end of the case.

Questions:

Imagine you are a team of senior research scientists at the initial planning phase of Biosphere 2. What kinds of specific conditions would be needed in Biosphere 2 to make it possible to sustain eight people for the rest of their lives? You might consider the following questions and sources of information:

- "Ecological services" as described in the article **Ecosystem services: Benefits supplied to human societies by natural ecosystems** by Daily et al. (1997).
- Should the eight researchers' diets be vegetarian or meat-based? What difference would this make?
- Are the ecosystem types shown in Fig. 2 above sufficient to sustain people?
- Should animals be included in Biosphere 2? If so, what kinds?
- How might driving a car in Biosphere 2 affect the sustainability of the eight people?

Part II. A Delicate Balance

On October 12, 1999, Secretary-General of the United Nations, Kofi Annan, welcomed Adnan Nevic of Sarajevo, Kosovo, into the world, marking the birth of the six billionth living human. The event rejuvenated long-standing debate about how many people the Earth can support before exhausting the supply of natural resources and a clean environment. Most current estimates project a human carrying capacity, or the number of people that the Earth can support, at around 12 billion, occurring sometime within the next century (Cohen 1995).

The difficulty of determining the uppermost limit of human population is that the human carrying capacity changes through time and will likely rise to some extent with increasing population. Former President George H.W. Bush argued that "Every human being represents hands to work and not just another mouth to feed" (Bush 1991). This suggests that more people can acquire more resources to sustain larger populations, such as building irrigation canals to grow more food or building more housing. More people may lead to greater ingenuity and technical innovation, such as medical advances and genetically engineered crops. However, others have pointed out that this view does not specify the cultural, environmental, and economic resources available to make additional hands productive and, therefore, does not specify by how much the additional hands can increase human carrying capacity (Cohen 1995). For example, there is no advantage to more people in drought-stricken countries where irrigation canals are useless. There is no advantage to more people if raw materials, such as lumber, are not available to build homes. The advantage of additional scientists may be limited if research funding declines.

Potential limits to human population size depend critically on the relative balance between the rate of consumption of natural resources and the production of waste versus the rate at which natural resources and services are provided by the planet. Joel Cohen of Rockefeller University argues that "To believe that no ceiling to population size or carrying capacity is imminent entails believing that nothing in the near future will stop people from increasing Earth's ability to satisfy their wants by more than, or at least as much as, they consume" (Cohen 1995). He emphasizes this point poignantly: "How many people the earth supports depends on how many people will wear cotton and how many polyester; on how many will eat meat and how many bean sprouts; on how many will want parks and how many will want parking lots. These choices will change in time and so will the number of people the Earth can support" (Cohen 1995).

Not only does human sustainability on Earth depend on population size, it also depends on rates of material consumption and waste production by the population. Although human population growth rates are often highest in developing nations, income and material consumption are often more than an order of magnitude greater in wealthy industrialized nations, such as the United States, Japan, Canada, France, Germany, and England (see Table 1).

Table 1. Population growth rates and doubling times of selected countries for year 2001.
Data Sources: **Population Reference Bureau** and **World Bank**.

Country	Continent/Region	Annual Population Increase (%)	Population Doubling Time (yr)*	Per-capita purchasing power (1999 $)
Palestinian Territory	Middle East	3.7 %	19	NA
Oman	Middle East	3.5 %	19	NA
Solomon Islands	Oceana	3.4 %	20	2,050
Yemen	Middle East	3.3 %	21	730
Chad	Africa	3.3 %	21	840
Maldives	Asia	3.2 %	22	4880
Liberia	Africa	3.1 %	23	NA
Demo. Rep. Congo	Africa	3.1 %	23	590
Bhutan	Asia	3.1 %	23	1,260
Gambia	Africa	3 %	23	1,550
Mali	Africa	3 %	23	740
Saudi Arabia	Middle East	2.9 %	24	11,050
Guatemala	Central America	2.9 %	24	3,630
Pakistan	Asia	2.8 %	25	1,860
Honduras	Central America	2.8 %	25	2,270
Paraguay	South America	2.7 %	26	4,380
China	Asia	0.9 %	77	3,550
United States	North America	0.6 %	116	31,910
France	Western Europe	0.4 %	174	23,020
Canada	North America	0.3 %	231	25,440
Japan	Asia	0.2 %	347	25,170
United Kingdom	Western Europe	0.1 %	693	22,220
Italy	Western Europe	0 %	—	22,000
Greece	Western Europe	0 %	—	15,800
Poland	Eastern Europe	0 %	—	8,390
Sweden	Western Europe	0 %	—	22,150
Germany	Western Europe	-0.1 %	—	23,510
Czech Republic	Eastern Europe	-0.2 %	—	12,840
Latvia	Eastern Europe	-0.6 %	—	6,220
Russia	Eastern Europe	-0.7 %	—	6,990
Ukraine	Eastern Europe	-0.7 %	—	3,360

* Population doubling time is calculated as $t = \ln(2)/\ln(R)$, where *ln* = natural logarithm and *R* is popuation growth rate, which is equivalent to 1 + the fractional annual population increase.

To the extent that material consumption drives energy use, resource extraction, pollution, climate change, and landfill buildup, this means that industrialized nations have a larger per-capita impact on the environment (Brown et al. 1993, Herendeen 1998). The United States, by virtue of its massive per-capita consumption of natural resources and energy and its generation of CO_2 and waste, could be considered the most overpopulated country in the world in terms of environmental impact (Cohen 1995, Gardner and Sampat 1999).

Material Consumption and Pollution

Earth is strained by rapidly rising per-capita consumption, especially in industrial nations. Modern societies are consuming more natural resources and generating more waste than at any time in human history. For example, the average American uses 101 kilograms of materials in a given day in both direct consumption of goods and indirect consumption of materials required to make those goods (Gardner and Sampat 1999).

Material consumption is having significant impacts on the global environment. The global cycles of carbon and nitrogen are now dominated by human inputs, often eclipsing natural rates of movement of material by the biosphere and geosphere. From 1860 to 1991, the human population quadrupled, whereas energy consumption rose 93 fold (Cohen 1995). Most of this energy consumption is provided by fossil fuels combustion, which releases greenhouse gases like carbon dioxide into the atmosphere. In 1998, the top five industrial polluters alone—USA, China, Russia, Japan, and India (see http://cdiac.esd.ornl.gov/trends/emis/graphics/top20_1998.gif)—contributed more than half of global carbon emissions (Marland et al. 2001). The anthropogenic rise in carbon dioxide is occurring at a rate hundreds of times faster that any change seen during the Pleistocene Epoch (the most recent Ice Age) spanning the past 1.8 million years. By the end of the 21st century, atmospheric carbon dioxide levels will reach the highest levels seen in the last 30 million years (Pearson and Palmer 2000).

Humanity also strongly modifies the productivity of the biosphere through land use change and the addition of nutrients. Stanford ecologist, Peter Vitousek, determined that humans co-opt approximately 40% of total plant productivity on Earth (Vitousek 1986). Moreover, the exponential growth of nitrogen fertilizers following WWII now rivals nitrogen fixation by the biosphere in terms of the amount of new nitrogen introduced into the environment each year, leading to chronic problems of acid rain, eutrophication, and the destruction of stratospheric ozone (Vitousek 1994).

Lastly, wood comprises one fraction of the materials consumed by humans, and current logging rates in tropical countries to supply this demand is leading to record rates of rainforest destruction (Laurance 1997, Laurance 2000). Given that the tropics may support 50 to 80% of the world's biodiversity, destruction of this habitat may be driving eight to 11 species extinct per day (Wilson 1992).

Clearly, consumption in the industrialized world is rapidly converting natural capital to material goods, resulting in declines in primary forests, biodiversity, and clean air and water, and increases in ozone, atmospheric pollution, and solid-waste landfills. At the global level, steady changes in these indicators of environmental health all suggest that rates of material consumption are not sustainable in the long term

Can we Measure Sustainability?

Instead of the difficult task of estimating the human carrying capacity (number of people per total land area of Earth), Mathis Wackernagel and colleagues at **Redefining Progress** developed the concept of "*ecological footprint*" to quantify humanity's long-term impact on the global environment (Wackernagel and Rees 1996). The ecological footprint represents the inverse of carrying capacity because it quantifies the amount of land area that is required to sustain the lifestyle of a population of any size—an individual, household, community, city, country, or world.

For example, consider the ecological footprint of one human. Given Earth's 8.9 billion hectares (where a hectare is an area equal to a 100-m x 100-m square) of productive land and its 6 billion human inhabitants, the average ecological footprint should be about 1.5 hectares per person if we assume that land use should be distributed equitably among all of the planet's citizens. This per-capita footprint provides an unambiguous benchmark with which to assess the long-term sustainability of population growth and material consumption. Individual footprints below 1.5 hectares are sustainable whereas footprints above 1.5 hectares are not. Footprint calculations by Wackernagel and Rees (1996) suggest that the individuals in industrialized countries often have footprints as large as four to 10 hectares.

Wackernagel and Rees (1996) posed a thought experiment analagous to Biosphere 2 to illustrate the concept of sustainability and the ecological footprint. Imagine you could cover your town with a big glass dome that sealed off the area of the town and its immediate atmosphere from the rest of Earth. The question of sustainability becomes this: How large does the dome have to be and what sorts of land use types need to be included to ensure the survival of all inhabitants? The more your town is comprised of *industrial capital*, such as asphalt, buildings, and vehicles, the more difficult it becomes to sustain life because of the lack of *natural capital*, such as land to grow food and plants to provide life-supporting oxygen and remove life-threatening carbon dioxide. It is clear from this example that every urban center is unsustainable, as indicated by massive fluxes of energy, water, food, and clean air into cities and exports of solid and gaseous waste out of cities. Sealing off an urban center under a glass dome would be fatal for its inhabitants. The ecological footprint of cities is vastly larger than the geographic area in which they lie (Wackernagel and Rees 1996).

In fact, Wackernagel and Rees estimated that if all global citizens aspired to the American lifestyle and attendant levels of consumption, we would require two additional Earths to provide enough land area to supply natural resources and to absorb industrial waste! In a startling new study, their work suggests that the ecological footprint of humanity began to exceed the capacity of the Earth to supply resources in the early 1980s (see Fig. 1 in Wackernagel et al. 2002).

Understanding the interactions of population growth and material consumption presents a challenging study of the impacts of humans on the global environment and the long-term sustainability of humanity:

- How does material consumption impact the environment?
- Is material consumption of greater significance to environmental impact than population growth?
- How can we can quantify the ecological footprint to measure sustainability?
- How do our lifestyles, especially the attributes of living in a wealthy, suburbanized, automobile-dependent culture, impact the global environment and the ability for citizens in other countries to acquire a fair share of Earth's resources?
- What kind of global environmental impacts can we envision as developing nations aspire to achieve industrial economies similar to that of the United States?

Part III. Benchmark for Improvement

To what extent do our lifestyles impact the environment and contribute to the number of people the Earth can support? How can the concept of the ecological footprint be used to measure the impacts of our personal consumption on the environment? Is your lifestyle sustainable? In this case study, you will have the opportunity to calculate your ecological footprint based on your own consumption of resources. You will be able to judge whether your lifestyle is sustainable relative to the global benchmark of 1.5 hectares per person.

Part IV. Calculating Your Footprint

To complete this case, you will need to record your consumption of energy and materials in each of the following six categories: food, housing, transportation, goods, services, and waste.

The following **table** provides a guide for the specific items and quantities you should monitor over the time span of two weeks or a month. Once you have tallied your monthly consumption of these items, use the footprint spreadsheet to directly convert the amount of goods and services you consume and waste you produce into an area of land needed to support them. If you assess your consumption of these categories over two weeks, it is important that you double these values to convert them to monthly values for the spreadsheet.

Downloading the Miscosoft Excel spreadsheet

- ***For PC users***, right click your mouse on the **footprint.xls** link, choose the "Save link as" option, and select a directory you want to save the spreadsheet to.
- ***For Mac users***, click your mouse over this link, choose the "Save link as" option, and select a directory you want to save the spreadsheet "ecological footprint.xls" to.

Using the Spreadsheet

You will use a spreadsheet developed by Mathis Wackernagel and colleagues at Redefining Progress (Wackernagel et al. 2000). The following description provides an overview of how the spreadsheet works:

- Open the footprint.xls spreadsheet using Microsoft Excel.
- Data are entered in the *blue cells*. Notes are indicated by the *red tabs*. You can acces the information in the note by moving your mouse over the cell with the red tab.
- In cell H4, you enter whether you want to use metric or US standard units. In cell D8, you enter the number of people for which you are calculating a footprint. If you are only accounting for your personal lifestyle, please enter 1.
- Next, you will see the six consumption categories: food, housing, transportation, goods, services, and waste. Examine the kinds of information that you need to enter in the blue cells. These data are what you will need to keep track of over the month that you are assessing your footprint.
- Note that the units of each of the categories are presented in column C.
- The spreadsheet calculates the amount of land required to sustain each of these consumption categories. Notice in columns G-L that there are six Earth surface categories that can be used to produce materials consumed or to absorb the waste of producing and using them: fossil energy land, arable land, pasture land, forest land, built-up land, and sea. Fossil energy land is the amount of land surface covered with forests that is required to absorb CO_2 emitted from the combustion of fossil fuels. Living sustainably requires that the amount of CO_2 gas in the atmosphere does not rise as a result of fossil fuel combustion. Arable and pasture land and the sea are required for food production. Forests are required for timber and paper resources. Built-up land is required for housing, transportation, and the production/processing of materials and energy.
- When all of your data are entered, the spreadsheet converts the amount of materials and energy consumed and wasted into land areas for each of the six land use types.
- The spreadsheet then totals the land areas required to support the six consumption categories and presents the ecological footprint in cell G148.

How does the ecological footprint work? Understanding the spreadsheet calculations

Using the spreadsheet to calculate an ecological footprint does not require a detailed understanding of how the spreadsheet converts material and energy consumption and waste into land area. However, examining the relationship between land area and material and energy consumption provides a rich understanding of how humanity impacts the environment—impacts that we may not commonly think about.

The following links describe these calculations in depth, showing the innovative approaches that Wackernagel and colleagues developed to assess individual sustainability.

- **Introduction to calculations**

Specific Notes about the Spreadsheet Calculations

The following section describes how specific land use types are important for producing the materials and absorbing waste in the spreadsheet. As explained below, some calculations are modified from the general description presented in the "Introduction to calculations" page. By clicking on the red triangles in the spreadsheet, you can show comments describing each calculation.

- **Food**
- **Housing**
- **Transportation**
- **Goods**
- **Services**
- **Waste**

Other notes about the Spreadsheet Calculations

- **What are correction factors? Issues of indirect consumption and "bottom up" versus "top down" footprint calculations.**

- **What are equivalence factors? Why account for bioproductive land?**

- **What does the ecological footprint not account for? Is it an underestimate or overestimate of your true ecological footprint size?**

Tips for Determining Your Consumption of Resources

Depending on your living arrangements, it may be easy or challenging to account for your consumption of commodities like water, natural gas, and electricity. Some students live in houses where the quantities of these factors appear on monthly utility bills or meters outside the home that can be easily read. Other students live in large dorms where it is more difficult to determine one's personal consumption. Learning to to measure your consumption of water, electricity, and gas is a valuable first step in learning about your consumption patterns. Here are some tips for making this easy to do in case you don't have meters or monthly bills to use:

- **Water**— This is as simple as figuring out how much you use to drink, shower, flush the toilet, etc. Most toilets use up to 5 gallons per flush. Low-flow toilets may use as little as two gallons. Composting toilets use almost none. To measure shower and tap water consumption, you can place a two-liter bottle under faucets or shower and quantify the amount of water flowing over a given time. For example, let's say you placed a bottle under the shower tap for one minute and collected two liters. If you take 10-minute showers, you would have used 20L of water.

- **Electricity**— Determining electrical consumption requires that you analyze the power consumption of all the kinds of appliances that require electricity. The basic unit of power consumption is the kilowatt-hour (kWH). Most utility companies charge customers between 5-to-10 cents per kWH.

  Most appliances and lights are rated in watts (usually listed on the back of the appliance), so you can figure out how many watts you use per hour. For example, if you use a 100 watt bulb for 20 hours, that amounts to 2000 watt hours or 2 kilowatt hours (since electricity is about 5 cents per kilowatt hour, you would have used about 10 cents of energy).

  If you spend considerable time in particular buildings outside your dorm, such as a library, you may wish to estimate how much electricity and water you use in other buildings. The goal is not rocket-science accuracy; just do the best you can, and have fun estimating these. How many hours do you spend in these buildings? How many lights are in the ceiling of these rooms? How many other people are in the rooms at the same time (use the total # of people to calculate your contribution). For example, let's say you spend 5 hours/day in the library. Let's say there are 30 100-Watt bulbs in the room you work in there and that an average of 10 other students work in that room at any given time. Energy consumption per month from that room would be 30 bulbs * 100 watts/bulb * 5 hours/day * 30 days/month = 450 kilowatt hours/month for all 10 people, or 45 kilowatt hours for you alone. Pretty straightforward. You can do this kind of estimate for electricity in all the rooms you inhabit on campus.

- **Natural Gas, Oil, or Propane**— This category is required for measuring fossil gas or oil resources used for heating, but it does not apply to you if you use electricity, solar, or some other form of heating. It is a tough category to determine if you don't get a monthly bill for heating. The units of fossil fuels for heating are kind of strange: CCF (hundreds of cubic feet). To make matters more complicated, many dorms are often heated with radiators, which move steam through pipes to heat up rooms. Many campuses have steam plants that convert coal or natural gas to steam, which is piped all over campus for heating purposes. The only way to estimate this quantity might be to call the facility plant manager at your campus and ask if they have an estimate of the amount of fossil fuel consumed to heat your dorm. If not, just use the average quantity shown under the red note tabs in cells D64-D66.

  Note how this is a great learning experience. The fact that it might be really tough for you to nail down your exact consumption of fossil fuels required for heating underscores the ease with which people can be naive about their impacts on the environment.

- **Food**—The quantity of food you consume is relatively easy to determine if you shop for yourself. Most weights and volumes are listed on the packages, and produce and meats can be weighed on a scale. If you live on a meal plan, things get challenging. You will need to develop a system of writing down the foods and drinks that you consume and then estimating the weights and volumes of these materials. Use a scale, eyeball, or do whatever it takes. Just do the best you can.

- **Transportation**—This part is pretty easy. Most of the entries in the spreadsheet ask you how many miles you traveled and the fuel efficiency of the vehicle. For public transportation like planes, trains, and buses, the spreadsheet will ask you for person-miles or person-hours. This is how many miles or hours you alone traveled.

- **Goods and Waste**—Goods and waste will require that you estimate the weight of materials that you buy *over an average period of a month*. These are NOT the total amount of things that you own. Let's take clothing as an example to explore several ways of measuring goods. Say you buy one pair of pants, two shirts, and a pair of shoes every year. You could estimate the weight of all of these items and then divide this total weight by 12 to determine an average monthly weight. You would then enter these values in cells D99-D101. Or, you could measure just the weight of clothes that you buy in the month that you are analyzing your footprint. Note that in using this second strategy, your footprint could vary substantially, depending on whether or not it was a month you bought clothing. It's up to you to decide which method to use. Note that we did not consider the pile of clothing sitting in your closet that you already own. That is the culmination of many years of consumption. We are interested only in your current ***rate*** of consumption, not the total accumulated amount of material.

  The same principle holds for large items like appliances. It's best to average your monthly consumption over the lifespan of the product. For example, if you buy a refrigerator every 5 years, and it's weight was 300 pounds, your average monthly consumption would be 300lbs/5years/12 months = 5 lbs per month.

  Generally, "goods" are things that are pretty durable, whereas waste includes things that are more disposible. The waste category allows you to enter the fraction of different materials that you recycle.

  You will notice that some items like glass are listed both in goods and waste. You may wonder if this leads to double counting. For example, if you buy a soda in a glass bottle and then throw away the bottle, do you have to enter the weight in both the goods and waste categories? The answer is no—just enter it in one or the other, preferably the waste category since bottles are not generally considered durable goods. If you recycle all of your glass bottles, enter the weight in the spreadsheet and then enter 100% in cell H129.

- **Housing** —The units of housing are in square feet (sft), which is easy to measure using a tape measure. Remember that area can be calculated by multiplying the length and the width of a room and then adding up the areas of all of the rooms.

- **Services**—This is a fairly straightforward category; just enter the amount you spend each month on these services. One important caveat: Do not enter your tuition in the education category. This will make your footprint area erroneously large. This category is intended for educational services, like paying for someone to make photocopies.

Part V. Assignment

The assignment for this case includes three parts that will be turned in to your instructor:

- Together with other students, discuss the initial questions posed in Part I. Generate a detailed list of conditions required to sustain the lives of eight adults in a sealed environment like Biosphere 2 for the rest of their lives.

- Examine how sustainable your lifestyle is by estimating your ecological footprint. Keep track of your personal consumption of food, housing, transportation, goods, services, and waste using the spreadsheet and the instructions described above. The spreadsheet will give you a single estimate of your footprint in hectares or acres. This step will take about two to three weeks to complete. Please turn in a printout of the completed Excel spreadsheet.

- For the final part of the case assignment, use the information in your spreadsheet to answer the following questions and be prepared to discuss your answers in an open class discussion with your instructor and other students. Have fun with this discussion. The more thoughtful your answers and the more you prepare for the discussion, the better you and other students will understand the challenge of living sustainably and how society might take steps to do so.

Questions:

1. What parallels can you draw between sustaining the life of a person in Biosphere 2 and the sustainability of a person's lifestyle in the real world?
2. List the factors, from largest to smallest, that contributed to your footprint. What surprises you about this list?
3. In terms of the amount of land required to maintain your lifestyle, where might you consider your lifestyle to be sustainable? Not sustainable?
4. What specific actions could you take to reduce your footprint? If you were to take actions to reduce your footprint, in what ways would your lifestyle be fundamentally different? How realistic/achievable are these reductions?
5. How do you feel about the fact that the average footprint of a citizen in the United States is 4 to 10 hectares compared to the global average of 1.5 hectares? Why is this the case? Should anything be done about it? If so, what? What are the global consequences of being apathetic about this question?

Part VI. Epilogue: Life in a Dome

Columbia University Biosphere 2 Center was a living experiment of Wackernagel and Rees' big-glass-dome analogy. Eight people were sealed in the dome in 1991, but Biosphere 2 failed to sustain these eight scientists for even two years. By 1993, the oxygen concentration in the air inside Biosphere 2 fell to 14%—roughly equivalent to that at the peak of a 17,500-ft mountain (Nelson et al. 1993, Cohen and Tilman 1996). Atmospheric CO_2 rose to about 1700 parts per million (ppm), similar to a level last seen approximately 50 million years ago shortly after the extinction of the dinosaurs (Pearson and Palmer 2000). Nitrous oxide (N_2O), a trace gas emitted from the microbial decomposition of soil nitrogen, rose to 79 ppm—a level that can reduce vitamin B12 synthesis to levels that damage the brain (Cohen and Tilman 1996). Species extinctions were startling. Nineteen of the 25 vertebrate species in Biosphere 2 went extinct (Cohen and Tilman 1996). All pollinating species went extinct, in part because ants took over the insect world, forcing the researchers to pollinate plants themselves. In 1993, fresh air was pumped into Biosphere 2, the researchers were able to leave the system, and the test was over.

Why did Biosphere 2 fail? Much of the answer lies in the fact that researchers did not correctly judge the quantity of different ecosystems that were needed to sustain human life, and they did not anticipate how the entire system would adjust after it was sealed off. Specifically, too much soil was added in the tropical rainforest biome. The microbes in the soil, under the warm conditions in Biosphere 2, decomposed the soil carbon, releasing CO_2 to the atmosphere and consuming O_2. This, in part, drove down the quantity of breathable air and created a greenhouse effect with the high CO_2. Another factor that contributed to the decline in oxygen was the cement materials use to construct the foundation.

Other surprises included the collapse of the animal kingdom and the elimination of insect species valuable for ecosystem services like pollination. Ecosystem services are invaluble to humanity and, if degraded, can prove impossible or too costly to replace (Costanza et al. 1997, Daily et al. 1997).

Biosphere 2 and the ecological footprint are valuable lessons about sustainability. Even in our best attempt to sustain the lives of just eight people, we could not develop an artificial biosphere that was sufficient. Consider what would be required for a glass dome over your house, town, city, or country to perform any better.

VII. References

- Brown, L., H. Kane, and E. Ayers. 1993. *Vital Signs 1993: The Trends That are Shaping Our Future*. Norton, New York.
- Bruntland, G. 1987. *Our Common Future: The World Commission on Environment and Development*, Oxford: Oxford University Press.
- Bush, G.H.W. 1991. **Proclamation 6366—World Population Awareness Week**. *Federal Register*. October 30, 1991.
- Cohen, J.E. 1995. Population growth and Earth's human carrying capacity. *Science* 269:341-346.
- Cohen, J.E. and D. Tilman. 1996. Biosphere 2 and biodiversity: The lessons learned so far. *Science* 274:1150-1151.
- Corey, K.A. and R.M. Wheeler. 1992. Gas exchange in NASA's biomass production chamber. *Bioscience* 42(7): 503-509.
- Costanza, R., R. d'Arge, R. deGroot, S. Farber, M. Grasso, B. Hannon, K. Limburg, S. Naeem, R.V. O'Neill, J. Paruelo, R.G. Raskin, P. Sutton, and M. van den Belt. 1997b. The value of the world's ecosystem services and natural capital. *Nature* 387:253-260.
- Daily, G.C., S. Alecander, P.R. Ehrlich, L. Goulder, J. Lubchenco, P.A. Matson, H.A. Mooney, S. Postel, S.H. Schneider, D. Tilman, and G.M. Woodwell. 1997. **Ecosystem services: Benefits supplied to human societies by natural ecosystems**. *Issues in Ecology*. Number 2. Ecological Society of America.
- Galston, A.W. 1992. Photosynthesis as a basis for life support on earth and in space. *Bioscience* 42(7): 490-493.
- Gardner, G. and Sampat, P. 1999. Forging a sustainable materials economy. In *State of the World 1999*. Worldwatch Institute. Nortan Publishers, Washington, pp. 41-59.
- Herendeen, R.A. 1998. *Ecological Numeracy*. John Wiley and Sons. New York.
- Laurance, W.F. 1997. A crisis in the making: Responses of Amazonian forests to land use and climate change. *Trends in Ecology and Evolution* 13(10): 411-415.
- Laurance, W.F. 2000. Cut and run: the dramatic rise of transnational logging in the tropics. *Trends in Ecology and Evolution* 15(11): 433-434.
- Marland, G., T.A. Boden, and R.J. Andres. 1998. *Global, Regional, and National Fossil Fuel CO2 Emissions. Online Trends: A Compendium of Data on Global Change*. **Carbon Dioxide Information Analysis Center**. Oak Ridge, TN.
- Pearson, P.N. and M.R. Palmer. 2000. Atmospheric carbon dioxide concentrations over the past 60 million years. *Nature* 406: 695-699.
- Schwartzkopf, S.H. 1992. Design of a controlled ecological life support system. *Bioscience* 42 (7): 526-535.
- Vitousek, P.M. et al. 1986. Human appropriation of the products of photosynthesis. *Bioscience* 36(6): 368-376.
- Vitousek, P.M. 1994. Beyond global warming: Ecology and global change. *Ecology* 75(7): 1861-1876.

- Wackernagel, M. and W. Rees. 1996. *Our Ecological Footprint*. New Society Publishers. Gabriola Island, BC.
- Wackernagel, M., A. Callejas Linares, D. Deumling, M. Antonieta Vásquez Sánchez, I. Susana López Falfán, and J. Loh. 1996. *Ecological Footprints and Ecological Capacities of 152 Nations: The 1996 Update*. **Redefining Progress**.
- Wackernagel, M., R. Dholakia, D. Deumling, and D. Richardson. 2000. *Ecological Footprint Spreadsheet*, v 2.0. **Redefining Progress**.
- Wackernagel, M., N.B. Schulz, D. Deumling, A.C. Lineras, M. Jenkins, V. Kapos, C. Monfreda, J. Loh, N. Myers, R. Norgaard, and J. Randers. 2002. Tracking the ecological overshoot of the human economy. *Proceedings of the National Academy of Sciences*. 99(14): 9266-9271.
- Wilson, E.O. 1992. *The Diversity of Life*. W.W. Norton and Company, Inc. New York.

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Consumption categories and units

1. FOOD	**Units**
Enter percentage of food purchased that is wasted rather than eaten in your household.	*%*
How much of the food that you buy is locally grown, unprocessed, and in-season?	%
Veggies, potatoes, & fruit	[pounds]
Bread and bakery products	[pounds]
Flour, rice, noodles, cereal products	[pounds]
Beans and other dried pulses	[pounds]
Milk, cream, yogurt, sour cream	[quarts]
Ice cream, other fozen dairy	[quarts]
Cheese, butter	[pounds]
Eggs [assumed to be 50 g each]	[number]
Meat	
Pork	[pounds]
Chicken, turkey	[pounds]
Beef (grain fed)	[pounds]
Beef (pasture fed)	[pounds]
Fish	[pounds]
Sugar	[pounds]
Vegetable oil & fat	
solid	[pounds]
liquid	[quarts]
Tea & coffee	[pounds]
Juice & wine	[quarts]
Beer	[quarts]
Garden [area used for food]	[sqr ft]
Eating out [complete meals]	[$]

2. HOUSING	**Units**
House [living area]	
brick house	[sqr ft]
wooden house (US standard)	[sqr ft]
Yard [or total lot size incl. building]	[square ft]
Hotels, motels	[$]
Electricity (also check composition)	[kWh]
enter as fraction. ex. 25% = 0.25	
thermally produced (fossil and nuclear)	%
lower course hydro	%
high altitude hydro	%
PV solar (on exisiting roof areas)	%
PV solar (on newly built-up area)	%
wind	%
geothermal	%
biomass	%
Fossil gas (natural gas)	
city gas	[CCF]
bottled liquid gas	[pounds]
Liquid fossil fuel (oil)	
in volume	[gallons]
in weight	[pounds]
Coal	[pounds]
Water, sewer, garbage service	[$]
Straw	[pounds]
Firewood	[pounds]
Construction wood & furniture	[pounds]
Major appliances	[pounds]
Small appliances	[pounds]

3. TRANSPORTATION	**Units**
Bus, intracity transit	[pers*miles]
Bus, intercity	[pers*miles]
Train, transit	[pers*miles]
Train, intercity (Amtrak)	[pers*miles]
Taxi /rental/other's car	[miles]
average fuel efficiency	[mpg]
Car (your own)	[miles]
average fuel efficiency	[mpg]
Motorcycle	[miles]
average fuel efficiency	[mpg]
Parts for repair	[pounds]
Airplane	[pers*miles]
(e)conomy, (b)usiness or (f)irst class?	

4. GOODS	**Units**
Clothes (if bought used, count them at 1/3 of their true weight)	
cotton	[pounds]
wool	[pounds]
fossil based (synthetic)	[pounds]
Durable paper products (books) and hygenic paper products (toilet/tissue paper)	[pounds]
Tools, metal items	[pounds]
Leather	[pounds]
Plastic products and photos	[pounds]
Computers and electronic equipment	[pounds]
Porcelain, glass	[pounds]
Medicine	[pounds]
Hygiene products, cleaning stuff	[pounds]
Cigarettes, other tobacco products	[pounds]

5. SERVICES (rough estimates)	**Units**
Postal services	
international	[pounds]
domestic	[pounds]
Dry cleaning or external laundry service	[$]
Telephone, electronics, photo equipment	[$]
Medical services and medical insurance	[$]
Household insurances	[$]
Entertainment	[$]
Education*	[$]

*Please note that education does not include tuition costs. These are educational services, like paying for photocopies.

6. WASTE (assuming everything compostable is composted, and waste equals packaging)	**Units**	**% recycled**
Household waste:		
paper	[pounds]	%
aluminum	[pounds]	%
magnetic metal	[pounds]	%
glass	[pounds]	%
plastic	[pounds]	%

How does the ecological footprint work?
Understanding the spreadsheet calculations

Consumption of food, housing, transportation, goods, services, and the generation of waste all require energy and land. These are represented in columns G-L in the spreadsheet. For example, vegetables (row 21) require arable land on which to grow (column H). However, they also require fossil fuels for fertilizer, tractors, and trucks to ship produce to markets. Because the ecological footprint area is measured in hectares, we need a method for converting fossil energy used into land area. Wackernagel and Rees (1996) assume that to live sustainably, all CO_2 emitted from the combustion of fossil fuels must be fully absorbed by vegetation (e.g., forests). The greater the amount of fossil fuels used, the greater the land area required to support the trees needed to absorb the CO_2. Without this CO-absorbing capacity, atmospheric CO_2 will rise and possibly lead to climate warming. By definition, this is not sustainability.

The amount of land needed to support fossil fuel used (column G) can therefore be calculated using the following formula (for this and subsequent equations, each term is defined in words on the first row, and the units of each term are shown in the second row):

$$\begin{array}{ccccccccc} \text{Land area} & = & \begin{array}{c}\text{Carbon}\\ \text{sequestration ratio}\end{array} & * & \begin{array}{c}\text{Energy}\\ \text{intensity ratio}\end{array} & * & \begin{array}{c}\text{Consumption quantity}\\ \text{in metric or US}\\ \text{standard}\end{array} & * & \begin{array}{c}\text{Metric conversion}\\ \text{factor, if needed}\end{array} \\ m^2 & = & \frac{m^2}{Gj} & * & \frac{Gj}{Kg} & * & Kg & * & \end{array}$$

where m^2 = a square meter of land; Gj = gigajoules or 10^{15}joules, which is a unit of energy; and Kg = kilograms of material consumed. The *carbon sequestration ratio* is the amount of land area covered with forests needed to sequester the amount of CO_2 released from the production of one Gj of energy. Wackernagel and Rees (1996) estimate this quantity to be 0.141. The *energy intensity ratio* represents the amount of energy required to produce and transport a kilogram of material, and this quantity changes for each material. This ratio is sometimes called the "*embodied energy*" of a product, reflecting all of the energy that went into making it. Notice how the units cancel by multiplying through the right hand side of the equation.

This approach can be extended to all of the other materials in the spreadsheet in terms of converting quantities of material consumed (items listed in the rows) into land area needed to support sustainable fossil fuel consumption, or "*fossil energy land*" (column G), *arable land* (column H), *pasture* (column I), *forest* (column J), *built-up land* (column K), and *ocean* (column L). The spreadsheet then adds up all of these land areas for all of the materials you consume and reports a total ecological footprint (cell G 148).

Please examine the links for each of the six consumption categories to see, specifically, how land area is calculated.

- **Food**
- **Housing**
- **Transportation**
- **Goods**
- **Services**
- **Waste**

1. FOOD CALCULATIONS

Fossil energy land

The calculation of fossil energy land needed to produce and transport food has two additional components. The first takes into account how much of your food is grown locally vs. processed and transported long distance. In cell F15, you are asked to enter an estimate of the fraction of your food that is fresh and locally grown. The average fraction for a US citizen is about 25% (selection "b"). If your fraction is smaller than this, the fossil energy required to ship and package your food goes up. Conversely, if your fraction of fresh, local food is larger than 25%, then the fossil energy required to ship and package your food is modified downward. The second modifier takes into account the waste factor for food that results from the harvesting and transporting processes (pre-purchase food loss). USDA figures reveal that there is, on average, a 10% decline from farm weight to retail weight. The 1.10 in the equations represents this value.

For the following food items, fossil energy land is calculated taking these factors into consideration:

- *Eggs* (cell G28)—The fossil energy footprint of eggs is based on a weight of 0.05kg per egg; 0.05 refers to 1 egg = 50g = 0.05 kg.
- *Sugar* (cell G35)—The fossil energy footprint of sugar is calculated using 3.85 = Energy intensity of sugar in (Calories/kg) and 4.18 Kj = 1.0 Calories, where Kj = kilojoules (a unit of energy).
- *Liquid vegetable oil* (cell G38)—The fossil energy footprint of liquid vegetable oil and fat: 0.8 = estimated density of vegetable oil (kg/l) in order to convert liters into kilograms (recall that density = mass/volume).
- *Tea and coffee* (cell G39)—The fossil energy footprint of tea/coffee is calculated using 18 = Energy intensity of tea/coffee in (Calories/kg) and 4.18 = Conversion factor for Calories to Kj.
- *Eating out* (cell G43)—The fossil energy component of eating out is calculated assuming that 20 Mj is consumed per meal eaten out (estimate).

Arable land

The quantity of arable land required to grow food follows a similar equation to that of fossil energy land:

Land area	=	Carbon sequestration ratio	*	Energy intensity ratio	*	Quantity in metric or US standard	*	Metric conversion factor, if needed	*	Waste factor, if needed
m^2	=	$\frac{m^2}{Gj}$	*	$\frac{Gj}{Kg}$	*	Kg	*		*	

where the *carbon sequestration ratio* is the amount of land of the crop required to sequester 1 Gj energy's worth of C. Here, energy means food calories. The *energy intensity ratio* is the amount of energy (in Gj, which is an energy quantity analogous to calories) produced by one Kg of crop. Again a waste factor of 10% is used to estimate the true amount of land needed to grow the crop.

The arable land footprint of the garden is simply the area of the garden. The arable land footprint of dining out is calculated as (2900/365)*(.5) = m^2 of arable land per meal. This value represents the footprint area of average per capita food consumption not dining out (2900) per day (÷365) based on items grown in arable land only, and assuming that each meal eaten out provides one half of the day's nutritional content (*.5).

Pasture

The quantity of pasture land required to grow food uses a simple equation:

Land area	=	Land requirement	*	Quantity in metric or US standard	*	Metric conversion factor, if needed	*	Waste factor, if needed
m^2	=	$\frac{m^2}{Kg}$	*	Kg	*		*	

where land requirement is the amount of land needed to produce one Kg of meat. This is estimated using USDA data on the number of animals per hectare and the amount of meat yield per animal.

The pasture land footprint of dining out is calculated as (11500/365)*(.5) = m^2 of arable land per meal. This value represents the footprint of average per capita food consumption without dining out (11500) per day (÷365) based on items grown in pasture only, and assuming that each meal eaten out provides one half of the day's nutritional content (*.5).

Sea

Calculating the quantity of ocean area required to produce fish employs the same equation as that of arable land:

Land area	=	Carbon sequestration ratio	*	Energy intensity ratio	*	Quantity in metric or US standard	*	Metric conversion factor, if needed	*	Waste factor, if needed
m^2	=	$\frac{m^2}{Gj}$	*	$\frac{Gj}{Kg}$	*	Kg	*		*	

OTHER SPECIFIC NOTES ABOUT FOOD:

1. ***Food source*** (cell B12): With the exception of the sub-categories 'Eating Out' and 'Garden Area,' all sub-categories in the FOOD section should include only food being brought into the household from an outside source (i.e., not homegrown food).

2. ***Units***: Most units for food items are shown in column C. For wine and juice (cell C40), a standard bottle of wine contains 0.75 liters or 0.75/1.06 = 0.7 quarts.

3. ***Food quantity consumed per month*** (cell D12): The following table reports average US per-capita food consumption data for 1996 from: USDA, Agricultural Statistics 1998, Table 13.5, "Per-capita consumption of major food commodities." You can compare your monthly consumption rate to these values to see how you compare to the average US citizen.

Food Item	**Average Monthly Per-Capita Consumption in US**
Veggies, potatoes, fruit	48.7 lbs
Bread and bakery products	7.8 lbs
Flour, rice, noodles, cereal products	8.9 lbs
Beans and other dried pulses	0.7 lbs
Milk, cream, yogurt, sour cream	9.1 quarts
Ice cream, other frozen dairy	1.2 quarts
Cheese, butter	2.7 lbs
Eggs	20
Meat	
Pork	3.8 lbs
Chicken, turkey	5.4 lbs
Beef (grain fed)	5.4 lbs
Beef (pasture fed)	NA
Fish	1.2 lbs
Sugar	5.5 lbs
Vegetable oil and fat	
Solid	2.5 lbs
Liquid	1.2 quarts
Tea and coffee	0.8 lbs
Juice and wine	3 quarts
Beer	7.3 quarts
Garden size	NA
Eating out	$68

2. HOUSING CALCULATIONS

Housing requires materials and energy for construction (the embodied energy) as well as energy for electricity, heating, and cooling.

Fossil energy land

The calculation of fossil fuel land for housing is similar to that of food, except that fossil fuels are required for both the construction and maintenance of housing.

Land area	=	Carbon sequestration ratio	*	Energy intensity ratio	*	Consumption quantity in metric or US standard	*	Metric conversion factor, if needed	*	Waste factor, if needed
m^2/yr	= m	$\frac{m^2}{Gj}$	*	$\frac{Gj}{^2\ house/yr}$	*	m^2 house	*		*	

The life-cycle embodied energy of a standard Canadian house with 350 square meters of living space adds up to 1,310 Gj (Canadian Mortgage and Housing Corporation, OPTIMIZE, 1991, researched by Sheltair). Because the life-expectancy of a brick building may be 70 years, the embodied energy is calculated as 1310 Gj/350 m^2/ 70yr = .0534 Gj/m^2/yr. The average life expectancy of a wood house is 40 years.

Hotel energy costs are estimated from the average resource use of households. Wackernagel et al. (2000) assume an average wooden house in the US (with the land) would cost 150,000 dollars and has 2000 square feet. This corresponds to a monthly mortgage cost of 1000 dollars. In addition, each square foot may use the equivalent of 36 Mj of energy per year, including hot water and electricity, or 3 per month times 2000 square feet = 6000 Mj/month, or 6 Mj per dollar. Apart from the energy aspect, if you enter 1000 dollars a month, you should get the same result as a 2,000 square foot house. If you delete the second term in the energy column (which corresponds to the 6 Mj per dollar operational energy), the energy column also should be the same.

Direct energy usage for a house can be used to calculate the fossil energy footprint (cell G54).

Land area	=	Carbon sequestration ratio	*	Energy intensity ratio	*	Consumption quantity in metric or US standard	*	Metric conversion factor, if needed	÷	Waste factor, if needed
m^2/yr	=	$\frac{m^2}{Gj}$	*	$\frac{Gj}{kWh}$	*	kWh	*		÷	$\frac{\text{kWh reaching house}}{\text{kWh sent to house}}$

In this calculation, 3.6 = energy intensity of production (Gj energy produced per kWh consumed), and 0.3 = amount of energy transfer due to energy loss in conversion from the primary energy source to electricity (in generating and delivering electricity, 70% of the energy is lost as heat due to the electrical resistance of power lines). You can see that dividing the quantity on the right by a 0.3 waste factor causes the ecological footprint to more than triple because of this wasted energy. Cell D54 = percent of total electricity generated from thermal sources. Note that a greater fraction of renewable energy would reduce the fossil fuel land footprint.

Additional heating may be provided by natural gas furnaces or oil furnaces (cells G63-65). For the carbon sequestration ratio, world average growing forests can absorb per hectare the carbon of 93 Gj/yr of gas. In Seattle, one hundred cubic feet (CCF) contains on average 1.1 Therms. One Therm contains 100,000 btus. This corresponds to 29.3 kWh (and cost in Seattle about 50 cents in 1999). Therefore, in this calculation, 10000/93000 gives the carbon absorption capacity of world average forests in [m^2*yr/Mj], 1.1 gives Therms per CCF, 29.3 gives kWh per Therm, 3.6 gives Mj/kWh, and 1/0.3048^3/100 translates m^3 into CCF. For home oil, the average fossil fuel footprint is 71 Gj per 10,000 m^2 a year. The energy intensity ratio is 35 Mj/kg to produce oil. The energy intensity of coal is 35 Mj/kg (cell G66). Firewood requires fossil land (cell G67) to absorb CO2 as well as forest land (see below).

Note also the fossil energy land needed to support consumption of water (for sewage), appliances, and computers (cells G71-74). Note how the energy intensity ratio changes from 5 MJ/pound for construction wood to 200 MJj/pound for computer equipment. This shows how energy intensive the production of electronics is.

Arable land

With the exception of straw bale insulation (not considered in this spreadsheet), little arable land is required for building or providing energy for housing. Here, straw is considered as a fuel source for heating. Straw is calculated at the rate the removed biomass can be replaced (to make sure there is no nutrient loss on the field where the straw is grown). As a first approximation, cereals biomass productivity is used as a proxy of bioproductivity potential. On world average land, straw productivity is approximately double that of its cereal harvest. Hence, the productivity is 2 * 2904 kg per 10,000 m^2 a year (cell H69).

Pasture

Little pasture land is required for building or providing energy for housing. Wackernagel and Rees (1994) assume that flooding of land for hydroelectric dams comes from this land use type. They estimate that 10000 m^2 of flooded pasture land can produce 15,000,000 Mj (or 15,000 Gj) per year (cell I56). To convert kWh to Mj, they use the conversion factor 3.6 = Mj/kWh.

Forest

Forest land contributes to the production, heating, and furniture of housing. The following calculation shows the amount of forest land required for the construction of wooden homes.

$$\begin{array}{c}\text{Land}\\\text{area}\end{array} = \begin{array}{c}\text{Roundwood}\\\text{productivity}\end{array} * \text{material intensity ratio} * \begin{array}{c}\text{Consumption quantity in}\\\text{metric or US standard}\end{array} * \begin{array}{c}\text{Metric conversion}\\\text{factor, if needed}\end{array} * \begin{array}{c}\text{Waste factor, if}\\\text{needed}\end{array}$$

$$\text{m}^2/\text{yr} = \frac{\text{m}^2\text{ land}}{\text{m}^3\text{ wood harvested}} * \frac{\text{m}^3\text{ wood used in construction per house}}{\text{m}^2\text{ area per average house lasting 40 years}} * \text{m}^2\text{ area of your house} * \quad * \frac{\text{m}^3\text{ wood harvested}}{\text{m}^3\text{ wood used in construction}}$$

An average Canadian house uses 23.6 m^3 of wood and may last 40 years (Government of Canada, 1991. The State of Canada's Environment. Ministry of Environment, Ottawa). The house may contain 150 m^2 of living space. For every 10,000 m^2, 1.99m^3 of timber can be grown per year (roundwood productivity); 2.5 is the ratio of roundwood needed per unit of construction wood.

Fuelwood land area is calculated using the following formula:

$$\text{Land area} = \text{Roundwood productivity} * \text{Wood density} * \text{Consumption quantity in metric or US standard} * \text{Metric conversion factor, if needed} * \text{Waste factor, if needed}$$

$$\text{m}^2/\text{yr} = \frac{\text{m}^2\text{ land}}{\text{m}^3\text{ wood harvested}} * \frac{\text{m}^3\text{ wood}}{\text{kg wood burned}} * \text{kg wood burned} * \quad * \frac{\text{kg wood harvested}}{\text{kg wood used}}$$

This calculation assumes a world average forest yield is 1.99 m^3 per 10,000 m^2 a year; 600 kg/m^3 is the average wood density; 0.53 is the waste factor for fire wood. It means that for each kg of firewood one needs 0.53 kg of roundwood. In this category, the waste factor is significantly smaller than 1 since about twice as much firewood than roundwood can be produced per m^2 a year.

The same formula can be used to calculate the amount of wood required for furniture. In this case wood is consumed into a product instead of being burned. The waste factor for furniture is considerably higher (2.5), reflecting the fact that it takes 2.5 kg raw roundwood to produce 1 kg of furniture.

Built-up land

Every home requires built-up land for the lot, the roads and sidewalks to access the lot, and for the facilities to produce electricity for the home. Wackernagel et al. multiply the yard space by 1.5 to include the access areas (roads and streets outside of the property, but still in service of the property) (cell K50). For the built-up area of hydroelectric dams, Wackernagel and Rees (1994) estimate that 10,000m^2 of dam facilities are required to generate 200,000 Mj of electricity (cell K55). Mj are converted to kWh using the formula 3.6 = Mj/kWh. For photovoltaic electricity, they assume that a home requires 24 m^2 of solar panels to produce 3000 kWh, and they divide this land area by 0.75 to account for embodied energy of making the solar panels (cells K58-59).

3. TRANSPORTATION CALCULATIONS

The ecological footprint of transportation is comprised of fossil fuel land to absorb the CO_2 emitted from burning fuel and the built-up land for highway infrastructure.

Fossil fuel land

Fossil fuel land for automobiles (cell G90) is calculated using the following formula:

Land area	=	Carbon sequestration ratio	*	Energy intensity ratio	*	1 / gas mileage	*	Quantity in metric or US standard	*	Metric conversion factor, if needed	*	extra embodied energy factor of car manufacture and maintenance
m^2/yr	=	m $\frac{m^2}{Mj}$	*	$\frac{Mj}{{}^2\ house/yr}$	*	$\frac{Liters\ gasoline}{km}$	*	km traveled	*		*	1.5

In a sustainable world, burning gasoline requires vegetated land to absorb CO_2 emissions. Wackernagel et al. estimate that 10,000 m^2 of forest can absorb the carbon emitted from the production of 71,000 Mj. The energy intensity ratio of gasoline is 35 Mj/l. Building and operating a car consumes substantially more energy than just the gasoline needed to power it. The embodied energy of automobile manufacture includes the energy needed to run manufacturing plants, refine petroleum, operate automobile dealers and parts stores, and run the construction equipment for building and maintaining highways.This embodied energy can be 50-63% higher than direct fuel use (Wackernagel and Rees 1994, Herendeen 1998).In this spreadsheet, Wackernagel et al. estimate an embodied energy factor of 1.50, or 150% direct fuel use is required to build and operate a car (cell G90). Fifteen percent is additional energy to build the car, and 35 % is the indirect energy consumed to build the physical infrastructure needed for automobile use (highways, bridges, etc.).

The energy intensity ratio for using buses (cells G84-85) is estimated to be between 0.92-3.77 Mj per km. Train energy intensity ratio (cells G86-87) varies between 2.46-3.09 Mj per km traveled, with the lower value associated with more efficient intercity travel.

Airline travel (cell G89) uses a similar formula to that of automobile travel:

Land area	=	Carbon sequestration ratio	*	Energy intensity ratio	*	Airplane speed	*	Quantity in metric or US standard	*	Waste factor, if needed
m^2/yr	=	$\frac{m^2}{Mj}$	*	$\frac{Mj}{Km\ traveled}$	*	$\frac{km}{hour}$	*	Person hours flown	*	class multiplier

Here, too, the carbon sequestration ratio for jet fuel is 10,000m^2/71,000 Mj energy. Jet airplanes require 3.34 Mj per kilometer distance traveled (energy intensity ratio). This ratio also includes the extra embodied energy factor of airport infrastructure. A typical flight speed is 800 = Km/hr. The class multiplier adjusts the footprint based on whether the flight is economy or business class. A multiplier of 0.95 is used for economy class and 1.1 for business class, reflecting the fact that it is less efficient to fly fewer business class passengers than economy class passengers. Person hours indicates the number of hours flown per person.

Built-up land

Built-up land required for automobile use can be calculated using the following formula and data.

$$\begin{array}{ccccccccccccc} \text{Land area} & = & \text{Total highway length} & * & \text{Conversion factor} & * & \text{Highway width} & * & \text{1/Vehicle miles traveled} & * & \text{Vehicle gas mileage} & * & \text{Personal gas consumption} \\ m^2 & = & \text{miles} & * & \dfrac{\text{meters}}{\text{miles}} & * & \text{meters} & * & \dfrac{1}{\text{miles}} & * & \dfrac{\text{miles}}{\text{gallon}} & * & \text{gallons (or liters)} \end{array}$$

The total rural and urban highway miles in the US is $3.9*10^6$ miles (Bureau of Trans. Stats.). There are 1609 meters/mile. The estimated average width of highways is 50 meters. Multiplying these three quantities yields a total highway area of $3.14*10^{11}m^2$. A total of $2.5*10^{12}$ vehicle miles are traveled per year in the US (Bureau of Transportation Statistics). An average car gets 20 miles/gallon, and there are about 3.78 liters per gallon. Note how all of the units cancel when multiplying through the right hand side of the equation. The personal footprint contribution for built-up area required for taxis and buses is assumed to be 5% and 2%, respectively, of the total distance traveled using these modes of transportation.

4. GOODS CALCULATIONS

Goods that we consume include a wide variety of natural and synthetic products. It is not surprising then that our footprint includes just about all land use types.

Fossil fuel land

Fossil energy is used to make each of the 11 products listed in the spreadsheet (cells B99-B109). The standard formula for estimating fossil fuel land applies here, but note that the energy intensity ratio changes for each product—from a low of 15 Mj/kg for porcelain and glass up to 200 Mj/kg for medicine. This reflects the fact that making goods like medicine and tools require significant inputs of energy to run machinery and labs.

Arable land

Arable land is required for people consuming cotton clothes and tobacco products. The productivity ratio for cotton is 10,000m^2 required to grow 636 kg (cell H99). 10,000m^2 of arable land will grow 1599 kg of tobacco (cell H109).

Pasture

Pasture land is required to raise sheep for wool and cattle for leather. The productivity ratio for wool is 10,000m^2 required to grow 10 kg (cell I100). 10,000m^2 of arable land will grow 57 kg of leather (cell I104). Note that animal products are much less productive per unit area of land because a farmer can grow significantly more plant crops than animals on a piece of land. This is a good example of the concept of <u>ecological efficiency</u>, where energy is lost at each step up the food chain.

Forest

Our direct consumption of paper products requires the harvest of trees.

$$\begin{array}{ccccccccccc}
\begin{array}{c}\text{Land}\\ \text{area}\end{array} & = & \begin{array}{c}\text{Roundwood}\\ \text{productivity}\end{array} & * & \begin{array}{c}\text{Paper conversion}\\ \text{efficiency}\end{array} & * & \begin{array}{c}\text{Consumption quantity}\\ \text{in metric or US}\\ \text{standard}\end{array} & * & \begin{array}{c}\text{Metric conversion}\\ \text{factor, if needed}\end{array} & * & \text{Waste factor, if needed} \\
\text{m}^2/\text{yr} & = & \dfrac{\text{m}^2\ \text{land}}{\text{m}^3\ \text{wood}} & * & \dfrac{\text{m}^3\ \text{wood}}{\text{kg paper}} & * & \text{kg paper} & * & & * & \dfrac{\text{kg wood }\underline{\text{harvested}}}{\text{kg wood used to make paper}}
\end{array}$$

As we saw with the construction of housing, 10,000m^2 of land can support approximately 1.99 m^3 roundwood. 1 m3 of roundwood can generate about 1000 kg of paper. 1.72 is the ratio of roundwood needed per unit of paper. This reflects a waste factor because not all of the parts of the wood are used in making paper.

Built-up land

This is one of the more difficult quantities to estimate because it incorporates many indirect sources of consumption. For example, when you buy a metal hammer, there are many factories that are required to mine the iron ore, convert the iron to steel, process the steel into hammers, ship the hammers to warehouses, and then ship the hammers to retail outlets. All of these steps required built-up land in terms of factories and transportation networks. We therefore need a way to convert the direct consumption of your hammer into land area required for all of these activities.

You can see how incredibly difficult this would be for any single person to accomplish, so Wackernagel et al. (2000) use several assumptions based on aggregate built-up industrial and commercial land in the US.

First, they assume that the amount of built-up land is directly proportional to the fossil energy area needed to manufacture the good. Thus, the calculation of built-up area for goods is going to involve a factor that multiplies the fossil energy land column (column G).

$$\begin{array}{ccccccc} \text{Built-up land area} & = & \text{fossil energy land} & * & \dfrac{\text{built-up land}}{\text{fossil energy required for built-up land}} & \div & \text{bioproductivity of land} \\ \text{m}^2 & = & \text{m}^2\ \text{FE land} & * & \dfrac{\text{m}^2\ \text{BU land}}{\text{m}^2\ \text{FE land}} & \div & 3.5 \end{array}$$

To calculate this factor, they use aggregate data for the entire US and the total US population. They estimate that 1100 m^2 is the per-capita built-up land footprint component of goods (which also includes wastes, sinces wastes are non-durable goods and the byproducts of durable goods). They divide 1100 m^2 by the sum of the fossil fuel energy required to support this built-up land (commercial and industrial energy use) and the waste land (landfills) generated by the built-up land. The values 1324 m^2 and 1196 m^2 are the fossil fuel areas of goods and waste, respectively. To standardize for the average productivity of land (see equivalence factors link), they also divide by 3.5, which reflects the fact that most built-up land is located on fairly bioproductive land comparable to arable land.

Note how the units cancel on the right hand side of the equation. Although many assumptions go into a calculation like this, it is valuable for seeing how indirect consumption can be quantified.

5. SERVICES CALCULATIONS

You might not often think that things like mailing a letter, dry cleaning clothes, going to a concert, or buying insurance can impact your ecological footprint, but they do, because all require energy and built-up land. Money paid to household insurance agents goes to replacing homes that were destroyed. Clearly, the indirect effects of our ecological footprints extend a long way!

Fossil fuel land

Fossil energy is used for each of the 8 services listed in the spreadsheet (cells B114-B121). The standard formula for estimating fossil fuel land applies here, but note that the energy intensity ratio changes for each service--from a low of 1 Mj/kg for telephone service up to 50 Mj/kg for international postal delivery. This reflects the fact that flying mail across the globe requires significant inputs of energy.

Forested land

The calculation for forested land generated by housing insurance payments assumes that half of the insurance money goes to administration, and the other half goes to insurance claims (rebuilding houses). The figures for rebuilding houses are taken from the hotel category (excluding the operational energy part). Since rebuilding of houses does not include land prices, the resource intensity is doubled (assuming that half the cost of housing is land, and half is construction).

Built-up land

Calculations of built-up land for services follow the same assumptions and data sources as those for goods. Please see the Goods Calculations for details.

6. WASTE CALCULATIONS

Throwing material away requires built-up land for landfills and the energy to transport these materials. It also requires energy and built-up land for the recycling process. In these calculations, you can enter data on how much of the following materials you recycle: paper, aluminum, other metals, glass, and plastic.

Note that you have to be careful not to double count goods that are both consumed and thrown away. This means that goods are entered in either the GOODS or the WASTE category, but not both. Here is a recommendation from Diana Deumling at Redefining Progress:

> "The idea behind the way we've set up these categories is that long-lasting or non-recyclable plastic, glass, metal, paper (books), etc., that are consumed should be entered into the Goods section. Also, short-lived paper like toilet paper or paper towels would get entered here."
>
> "In the Waste section, packaging and potential recyclables like aluminum, glass, newspaper, junk mail, etc., should be entered. This is partly because it is usually easier to estimate/weigh these amounts when they have entered the trash or recycling bin, rather than when they come into the house (for instance, the glass in a jar of mayonnaise, the plastic tray for a TV dinner, etc.)"

Calculations of built-up land for waste follow the same assumptions and data sources as those for goods. Please see the Goods Calculations for details.

What are correction factors? Issues of indirect consumption and "bottom up" versus "top down" footprint calculations

The ecological footprint is flexible enough to be calculated for any number of individuals, including whole countries. Wackernagel et al. (1996) have compiled footprints for 152 nations of the world. The household footprint that you are using for this project has been used to estimate the footprint of the entire United States.

The national footprint calculation for the US is very complete. In the national calculation, the total US footprint is divided into sub-footprints of Food, Housing, Transport, and Goods and Services, in a table called the "Land use consumption matrix." Because data on total food production and export, housing, transportation, energy, and commerce are readily available from sources like the US Departments of Agriculture, Housing and Urban Development, Transportation, Energy, and Commerce, it is relatively simple to capture most of the resource and energy flows in the economy, in the aggregate, including waste. This is called the "top-down" approach because it uses aggregate data to estimate an aggregate footprint for all of the people in the US. These aggregate data can be plugged directly into the spreadsheet, and an aggregate footprint for the US is calculated.

It is important to note that this kind of aggregate accounting is capable of quantifying "indirect consumption" that is difficult to quantify for individuals. For example, consider the following question: How much energy does it take to operate a car? Besides the obvious things that come to mind, like the amount of gasoline you put into a tank, there are many indirect energy requirements that buying, owning, and maintaining a car entails (Herendeen 1998). These include the energy to find, extract, and refine petroleum. They also include energy to build, maintain, and operate car manufacturing plants, retail dealers, and maintenance shops. These indirect uses of energy can total an *additional* 63% of the energy provided by the gasoline alone (Herendeen 1998). Thus, our consumption of energy for our automobiles extends far beyond the direct use of gasoline. Top-down national footprint calculations, because they account for all of the material and energy flows in the US, are good at quantifying indirect energy use.

The household footprint that you are using is relatively complete for a household consumer, and it represents a "bottom-up" approach. In contrast with the national footprint calculated with aggregate US data, the bottom-up approach misses some of the indirect flows of resources and energy because it is extremely difficult for you to account for these. In this respect, the individual footprint spreadsheet underestimates total material and energy consumption and waste production in the US. Put another way, if all 280 million citizens of the US were to complete individual spreadsheets and then we were to add up these individual footprints, the cumulative footprint of the US would be less than the footprint based on the aggregate data. Thus, there needs to be a way to correct this discrepancy between the top-down and bottom-up approach.

To do this, Wackernagel et al. (2000) filled out the household questionnaire using what we know to be the average consumption amounts for the different categories. They compared the footprint subtotals from the Food, Housing, Transport, and Goods and Services footprints derived from using this household questionnaire with the sub-footprints from the national calculation. They used the ratios between these categories to correct the household footprint. These ratios, or correction factors, shown in cells B137-I143 calibrate the household spreadsheet so that it accounts for indirect uses of materials and energy. These factors aren't perfect by any means, but it's the best method available for correcting the footprint to capture information that may be missed with the bottom-up approach.

Information Credit: This information was provided by Diana Deumling, Redefining Progress.

What are equivalence factors?
Why account for bioproductive land?

The ecological footprint research approach emphasizes looking at ecological limits, or the relationship between demand and supply or biocapacity. All footprint results are expressed in a standard unit of "global acres" or "global hectares" of bioproductive land. A global acre is an acre of biologically productive land that has been adjusted in area so that it reflects global average biomass productivity. This standardization is important to allow for meaningful comparisons of the footprints of different countries or regions, which use different qualities and mixes of cropland, grazing land and forest. For example, arable land in the US is significantly more productive than that in the desertifying Sahel region of sub-Saharan Africa.

Equivalence factors allow us to add up different categories of bioproductive land (cropland, grassland, forest) in a meaningful way, since these land uses have, on average, different inherent productivities. So we say that, on average, cropland is 3.2 times more productive than world average land, whereas forest is 1.8 times more productive, pasture is 0.4 times the average, etc. Cells L137-142 provide an estimate of the relative productivity of different land use types.

Built-up area is a bit of a strange category because it represents a use of nature that leads to the destruction of its biocapacity. In this way, it is distinct from the other footprint categories. Since most built-up area is on what was once high quality arable land, it is counted as if it were arable land. Thus, one acre of built-up area leads to the loss of a significantly larger surface when expressed in global acres.

Information Credit: This information was provided by Diana Deumling, Redefining Progress.

What does the ecological footprint not account for? Is it an underestimate or overestimate of your true ecological footprint size?

The ecological footprint does not document our entire impact on nature. It only includes those aspects of our waste production and resource consumption that could potentially be sustainable. In other words, it shows those resources that within given limits can be regenerated and those wastes that at sufficiently low levels can be absorbed by the biosphere. For all activities that are systematically in contradiction with sustainability, however, there is no footprint, since nature cannot cope with them. There is no sustainable regenerative rate for substances such as heavy metals, persistent organic and inorganic toxins, radioactive materials, or bio-hazardous waste. For a sustainable world, their use needs to be phased out. In other words, the above footprint calculation assumes that the person being assessed engages in none of these systematically unsustainable activities, be it for example the release of CFCs, the unsafe disposal of motor oil, or the purchase, use, and disposal of other harmful household chemicals.

Information Credit: This information was provided by the Ecological Footprint spreadsheet developed by Wackernagel et al. (2000).