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Paving the planet: impervious surface as proxy measure of the human ecological footprint

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Abstract: Fundamental questions regarding the human-environment-sustainability problematic remain contested. What are the relative roles of population, consumption, and technology with respect to sustainability? How can sustainability be measured? Numerous metrics have been developed to address these controversial questions including ideas of carrying capacity, environmental sustainability indices, and ecological footprints. This work explores the question: is pavement a proxy measure of human impact on the environment? We explore and evaluate the use of satellite derived density grids of constructed area (aka 'pavement' or 'impervious surface') in the calculation of national and subnational 'ecological footprints'. We generated a global constructed area density grid for the 2000–2001 period using satellite observed nighttime lights and a population count grid from the US Department of Energy. Satellite data inputs to the population product include MODIS landcover, SRTM topography and high-resolution imagery. Calibration of the global constructed area density product was derived from high-resolution aerial photographs. We demonstrate that a satellite derived constructed area per person index can serve as a proxy measure of ecological footprints at both the national and subnational level. This relatively simple and globally uniform measure of human impact on the environment correlates strongly with other more difficult to obtain measures.

Key words: DMSP OLS, ecological footprint, impervious surface, nighttime satellite imagery, sustainability index.

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I Introduction

> Humans have become a geologic agent comparable to erosion and eruptions … it seems appropriate to emphasize the central role of mankind in geology and ecology by proposing to use the term 'anthropocene' for the current geological epoch. (Crutzen and Stoermer, 2000)

The transition from the twentieth to the twenty-first century has seen an increasing awareness and concern about humanity as an agent of significant and perhaps irreversible damage to the Earth's ecological and environmental systems. Many of these concerns are enumerated and contrasted in august documents with names like 'The millennium ecosystem assessment' (MEA) and 'The United Nations millennium development goals report' (UNMDG). The eight human development goals outlined in the UNMDG (UN, 2008) are:

(1) eradicate extreme poverty and hunger;
(2) achieve universal primary education;
(3) promote gender equality and empower women;
(4) reduce child mortality;
(5) improve maternal health;
(6) combat HIV/AIDS, malaria, and other diseases;
(7) ensure environmental sustainability;
(8) develop a global partnership for development.

The eight key findings of the MEA (MEA, 2005) are:

(1) humans depend on nature and ecosystem services for their health and security;
(2) in the last half-century people have made unprecedented changes to the planet's ecosystems to meet rising demands for food, water, fibre, and energy;
(3) these changes have improved many people's lives; however, they have come at the expense of other primarily poor people and weakened nature's ability to provide vital ecosystem services;
(4) we are living beyond our means – 60% of the ecosystems studied are being degraded in unsustainable ways;
(5) pressures on ecosystems will grow significantly worse in the first half of the twenty-first century without dramatic changes in human attitudes and behaviours;
(6) there is growing concern that many ecosystems could reach 'tipping points' at which sudden and irreversible changes will have grave implications for human well-being;
(7) we have the technology and knowledge to make needed changes to protect both ecosystems and human well-being;
(8) in order to make these changes we must stop thinking about nature's services as free and limitless.

These two comprehensive documents outline in a broad way the essence of the human-environment-sustainability problematic that scientists, scholars, and citizens have struggled with for decades.

In January 2007 the All Party Parliamentary Group on Population, Development, and Reproductive Health of the UK Parliament issued a report titled 'The return of the population growth factor: its impact upon the millennium development goals' (McCafferty, 2007). Sadly, this report concludes that many of the millennium development goals will be difficult or impossible to achieve if current population growth rates continue in the least developed countries. Many argue that recent neglect and indifference to the role of basic demographic processes as they pertain to the millennium development goals has created formidable problems that are getting worse faster (Campbell *et al*., 2007). It is perhaps ironic that the goals of the UNMDG and MEA are shared by diverse groups such as women's rights activists, environmentalists, public health advocates, and those advocating population stabilization (Sachs, 2005), and many of the policies aimed at improving maternal health, reducing child mortality, and raising the education level of women result in reduced fertility rates, which in turn reduces the aggregate demand for food, water, fibre, and energy, the very activities which are damaging ecosystems.

Yet, despite the MEA conclusion that we have the technology and knowledge to protect ecosystems and insure human well-being, we are not pursuing and enacting these policies effectively. Public demand for the effective implementation of such policies seems to be driven more by physical evidence from earth scientists (eg, carbon dioxide (CO_2) concentrations in the atmosphere) than by social scientists (eg, population projections and poverty rates from the United Nations and others). We believe that remotely sensed imagery and derived data products are continuing to contribute to both the science and rhetoric that informs and drives public opinion regarding the human-environment-sustainability problematic.

Remotely sensed imagery has contributed to our collective understanding of human impacts on the Earth in many ways. The famous 'small blue planet' photograph (also known as 'Earthrise') taken by Apollo 8 astronauts in 1968 undoubtedly had a major influence on how we see ourselves in a larger context (Borman *et al*., 1968). Studies of deforestation in the Brazilian Amazon Basin that utilized satellite imagery from the Landsat platform garnered a great deal of public awareness (Skole and Tucker, 1993). Imhoff, Haberl, and others have used satellite imagery in conjunction with other data sources to follow up seminal questions raised by Vitousek *et al.* (1986) to explore what fraction of the world's net primary productivity from photosynthesis (NPP) is being consumed by human action (Imhoff *et al*., 2004; Imhoff and Bounoua, 2006; Haberl *et al*., 2007). Images of the 'Earth at night' derived from mosaics of hundreds of orbits of the Defense Meteorological Satellite Program's Operational Linescan System (DMSP OLS) have captured the public imagination and been incorporated into posters, news media weather presentations, and Google Earth (Sullivan, 1989; Elvidge *et al*., 1997a). These images of the Earth at night also contribute to many studies that measure and map human impacts on the Earth.

Since the turn of the twenty-first century, many studies have used nighttime satellite imagery to explore various facets of human-environment interaction (Doll, 2008). Not surprisingly, there have been many studies examining the significant relationship between nighttime lights data products and population parameters such as urban extent, urban sprawl, and exurban development (Imhoff *et al*., 1997; Elvidge *et al*., 1997b; Sutton, 2003; Small *et al*., 2005; Sutton *et al*., 2006). Urban areas are the most densely populated parts of the world and city lights data products have been used to map and estimate urban populations and intraurban population density (Sutton *et al*., 2001; 2003). Chris Doll has explored how the nighttime imagery serves as proxy measure for non-population related socio-economic phenomena such as CO_2 emissions and economic activity (Doll *et al*., 2000; Doll, 2003). Numerous studies have used the nighttime imagery to map, estimate, and/or measure various facets of economic activity at a range of spatial scales (Sutton and Costanza, 2002; Ebener *et al*., 2005; Sutton *et al*., 2007). Data sets derived from nighttime satellite imagery have been used to produce maps of impervious surface area (ISA; Elvidge *et al*., 2004). Impervious surface area has also been identified as an important environmental indicator variable (Arnold and Gibbons, 1996) for such things as its impact on water quality (Carlson, 2008).

These demonstrated capabilities that nighttime imagery of the Earth has for serving as a proxy measure of human impacts on the environment and other socio-economic phenomena have stimulated a lot of interest in the development of a NightSat mission (Elvidge *et al*., 2007a). A NightSat mission would be a satellite program designed explicitly to observe the Earth from space at night using sensors with higher spatial and spectral resolution. Recall that the DMSP OLS was designed in the late 1960s as a meteorological satellite to see sunlight and moonlight reflected off clouds.

Here we explore the utility of using a satellite derived density grid of constructed area in the calculation of national and subnational 'ecological footprints'. Human beings around the world build, use, and maintain constructed surfaces for shelter, transportation, and commerce. 'Paving the planet' is essentially a universal phenomenon that represents one of the primary anthropogenic modifications of the environment. Expansion in population numbers and economies combined with the popular use of automobiles has led to the sprawl of development and a wide proliferation of constructed surfaces. The percentage of people living in cities continues to rise, fed by the transport of food, water, fuel, consumer products, and building materials. There is wide agreement that humans have emerged as the primary agent of global change, but how can we measure and map our human ecological footprint and how does it vary spatially and temporally?

The ecological footprint is a well-established resource accounting tool that estimates how much biologically productive land and water area an individual or a geographically defined population uses to produce the resources it consumes and to absorb the wastes it generates based on prevailing technology and resource management practices (Wackernagel and Rees, 1996). Ecological footprint calculations have emerged as a valuable way to communicate and understand human impacts on the natural systems upon which we depend. They are also useful in modelling the longer-term impacts of human consumption – both on natural systems and society.

One of the principles in calculating ecological footprints is that populations utilize widely distributed resources. This is a key consideration for urban populations since the land used to generate their food, fibre, and wood is widely distributed and could be halfway around the world. Similarly, the emissions of CO_2 produced by fossil fuel burning are widely distributed. Another principle used in the calculation of ecological footprints is that it is not necessary to pinpoint the location that produces the resources used by a population. We pinpoint the location of where those resources are consumed using impervious surface as a proxy measure. Based on this measure of consumption, we calculate the quantity of land or water surface required to generate that quantity of consumption in terms of a normalized standard for biological productivity.

The Ecological Footprint's widely used normalized standard measurement unit is the 'global hectare' (GHA), defined as a biologically productive hectare with world average productivity. Kitzes *et al.* (2007) estimate that in 2003 the Earth made available 11.2 billion GHA while maintaining humanity's consumption depended on 14.1 billion GHA. Thus, humanity's resource consumption in 2003 was rated at 25% more than the Earth was able to produce (Figure 1) in the same year. Another way to look at this number is that it took the Earth 15 months to produce the resources used by humanity in a 12-month period. When consumption exceeds production the difference between the two numbers is made up by liquidating the Earth's ecological stores and the accumulation of waste products such as CO_2 in the atmosphere. These results and the ecological implications appear in a recent report issued by WWF International (2006).

While a growing number of organizations are producing estimates of ecological footprints, the Global Footprint Network (GFN) has emerged as the premier organization in establishing and updating the standards used and produces the most widely cited national and global ecological

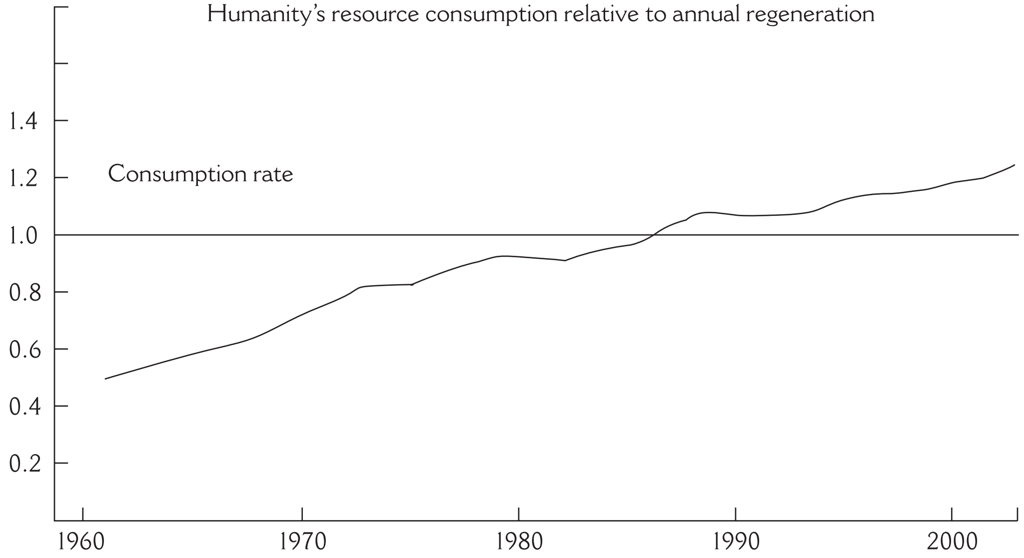


Figure 1 Chart showing the annual rate of humanity's resource consumption relative to the regeneration rate. Note that starting in the mid-1980s the consumption of resources began to exceed the annual rate at which resources are replenished

Source: World Wildlife Fund International (2006).

footprint estimates. The GFN assembles data from a wide range of sources to produce National Footprint Accounts, which record the resources consumed, CO_2 emissions, and calculations of the land and water areas that need to produce the resources and absorb the CO_2. The data sources and modelling continue to evolve under the auspices of a standards committee and the Global Footprint Network (Wermer, 2006). Each year national footprint accounts are updated to track the consumption of crop products, fibres, livestock, fish, timber, fuel wood, and CO_2 produced. From these values the model calculates the GHA utilization. The surface cover types that are tracked by national footprint accounts include cropland, grazing land, fishing grounds, forest, built-up land, and 'carbon land'. Land cover extents are drawn from multiple sources including CORINE, GAEZ, GLC 2000, and WCMC. Of these cover types, built-up land area estimates may be the least reliable data set, and weakest for global comparison (Kitzes *et al*., 2007).

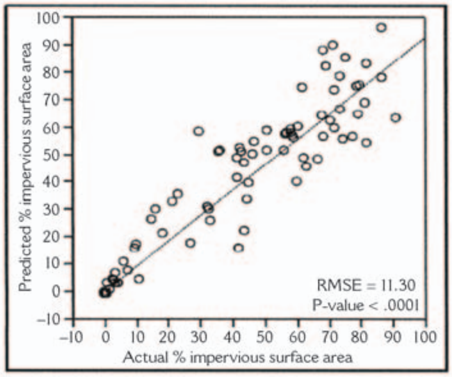
II Methods

In order to explore the potential of using satellite-based estimates of constructed area as a spatially disaggregated proxy for the human ecological footprint we developed a global grid of impervious surface area. This global grid of constructed area density is based on satellite derived nighttime lights and population count data for the United States only (Elvidge *et al*., 2007b). We produced this map of impervious surface by obtaining 80 high-resolution aerial photographs from 13 cities around the United States. For each photograph we classified 100 random points as 'impervious' (eg, rooftop, sidewalk, parking lot, roadway, etc) or 'not impervious' (eg, lawn, park, golf course, etc). The number of 'impervious' classifications for each photo was our calibrated value of the percentage impervious. We used a simple multivariate linear regression model to predict these calibrated values using only the light intensity value from the DMSP OLS derived city lights data product and the population count from the Landscan data product (Figure 2). We applied these regression parameters to the Landscan and DMSP OLS data products to produce an impervious surface data product. Comparisons of this impervious surface product to a finer resolution product produced by the United States Geological Survey demonstrated the validity of this approach (Yang *et al*., 2003; Elvidge *et al*., 2007b).

We applied these regression parameters on a global basis to produce a global density grid for constructed surfaces (Figure 3) for the 2000–2001 time period at ~1 km resolution (Elvidge *et al*., 2007b). The density of constructed surfaces (roads, buildings, parking lots, etc) was estimated using the brightness of 2000–2001 satellite observed nighttime lights (Elvidge *et al*., 1999) and the Landscan 2004 population count from the US Department of Energy (Bhaduri *et al*., 2002). The Landscan 2004 product is a spatial allocation of national and subnational population numbers. Satellite data inputs to

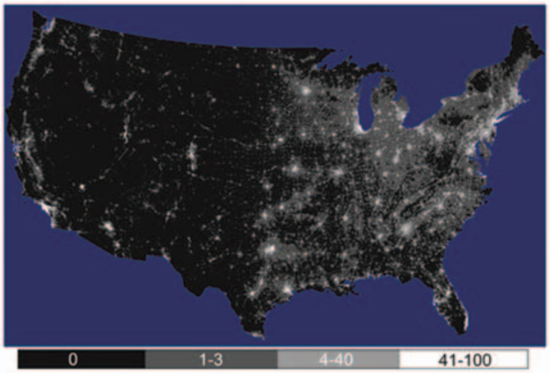
Step 1: 80 High Resolution Aerial Photographs are taken from transects of 13 cities of the U.S.

Step 2: 100 random points are classified as 'impervious' or 'not impervious' for each photo. The number 'impervious' is percent impervious for that square km



Step 3: The percent impervious for each photo is predicted using simple regression using the DMSP OLS dn value and the Landscan Pop count

ISA = 0.0795 (radiance) + 0.00868 (pop count)



Step 4: The regression parameters obtained from step 3 are applied to the DMSP OLS and Landscan data sets to produce a spatially explicit map of impervious surface

Figure 2 Methods for producing Impervious Surface Map

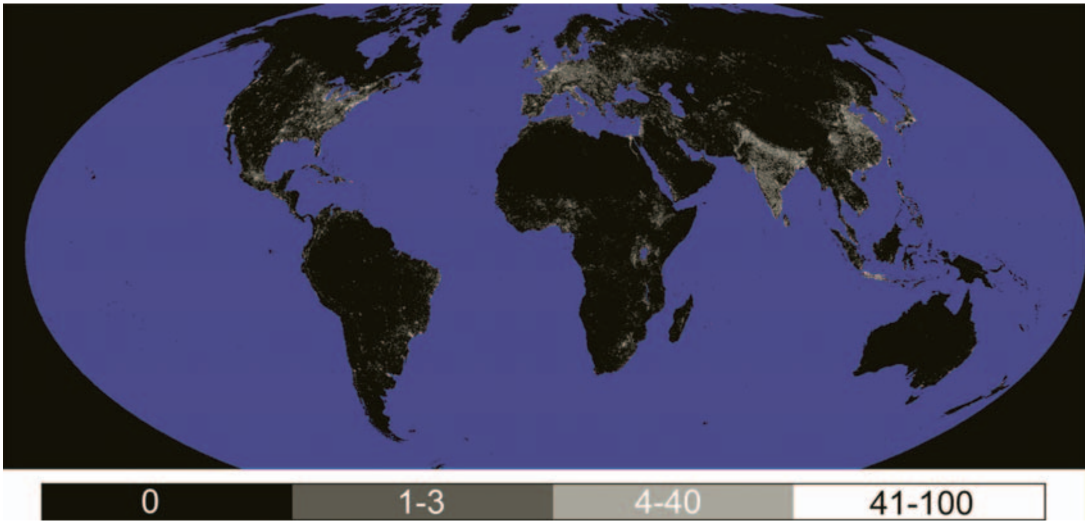


Figure 3 Satellite derived estimates of constructed area densities for 2000–2001 in a 1 km^2 equal area grid. The product values are in percent cover ranging from 0 to 100%. The figure shows these values aggregated into four greyscale levels

the Landscan 2004 include MODIS landcover, SRTM topography, and Controlled Image Base (CIB) high-resolution imagery from the US National Geospatial Agency (NGA). Nighttime lights were not used as input into Landscan 2004. The global constructed area product was calibrated using 2000–2001 Landsat derived 30 m constructed surface density data of the USA produced by the US Geological Survey and part of the National Land Cover Database (Yang *et al*., 2003).[1]

By dividing the constructed area by population count, it is possible to produce a disaggregated grid estimating the constructed area per person. By aggregating these values separately it is possible to estimate the constructed area per person at a variety of levels – including national and subnational administrative units. Figure 4 shows a scatterplot of the national level constructed area per person (in m^2) versus the ecological footprint per person (in GHA) for 149 countries (the GFN only included 149 countries). For constructed area per person values in the 30–60 m^2 range the ecological footprint remains relatively constant at about 1 GHA. Beyond 60 m^2 the ecological footprint increases along with the constructed area per person values in a largely linear manner. Table 1 summarizes the results of this analysis for 229 countries (for 149 of which the GFN had calculated a GHA/person value).

There are three potential ways in which the constructed area data may be used to improve either the quality or the spatial resolution of ecological footprints measurements:

(1) The quantity of built-up land is used as an input into the National Footprint Account estimation models and the measure presented here is an improvement on existing measures.

(2) As Figure 4 and Table 1 show, it is possible to estimate national level ecological footprints based on the constructed area per person metric. This relationship can be used to estimate and evaluate the ecological footprints for the 80+ countries and small islands (eg, Brunei, Oman, Seychelles, Aruba) not covered by the GFN estimates.

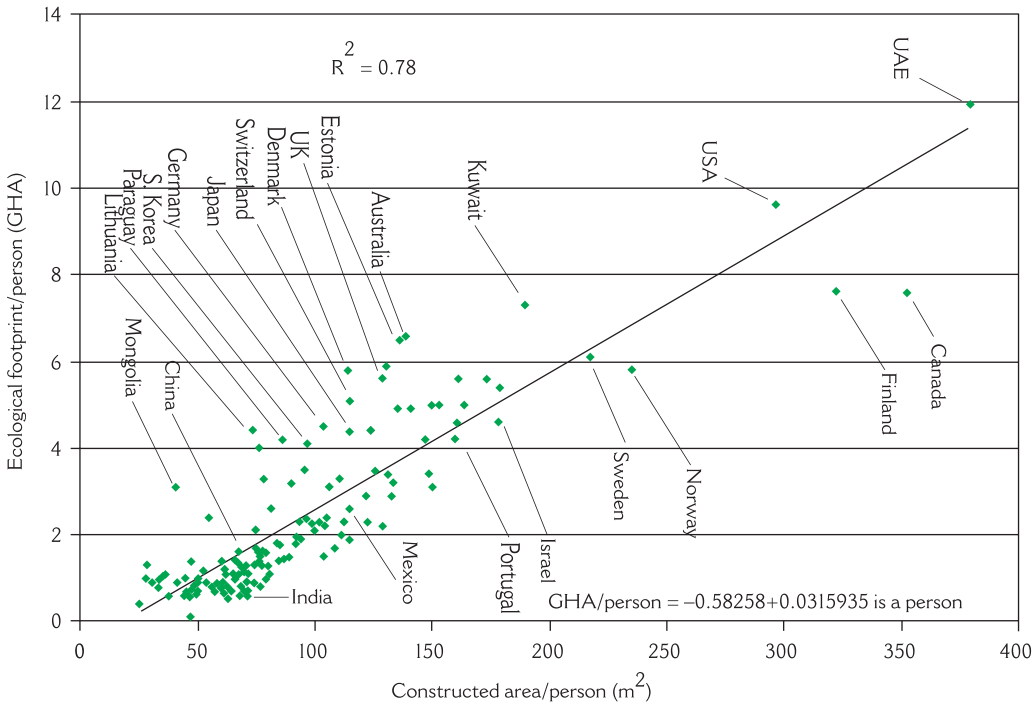


Figure 4 Constructed area per person versus ecological footprint per person for 149 countries

Table 1 National summary of population, impervious surface, and ecological footprints

Country	ISA (km^2)	Population 2004 (LandScan)	ISA/person (m^2)	GHA/person (Global Footprint Network)
China	87181.83	1,292,548,864	67.45	1.6
India	81221.36	1,058,349,824	76.74	0.8
United States	83881.07	282,575,328	296.84	9.6
Indonesia	16490.32	230,000,208	71.70	1.1
Brazil	17766.32	177,885,936	99.87	2.1
Pakistan	10665.68	150,465,168	70.88	0.6
Bangladesh	8878.25	140,275,504	63.29	0.5
Russia	17134.97	138,947,840	123.32	4.4
Nigeria	7668.17	125,118,728	61.29	1.2
Japan	13990.28	122,192,928	114.49	4.4
Mexico	11853.56	103,608,488	114.41	2.6
Germany	8499.5	82,406,312	103.14	4.5
Vietnam	5980.88	81,249,416	73.61	0.9
Philippines	5428.21	80,687,360	67.27	1.1

(*Continued*)

Table 1 *Continued*

Country	ISA (km^2)	Population 2004 (LandScan)	ISA/person (m^2)	GHA/person (Global Footprint Network)
Egypt	5745.43	75,240,640	76.36	1.4
Ethiopia	4096.03	71,446,352	57.33	0.8
Turkey	4987.58	66,874,440	74.58	2.1
Iran	6949.2	66,604,152	104.34	2.4
Thailand	5555.84	64,418,264	86.25	1.4
France	9536.85	59,497,124	160.29	5.6
United Kingdom	7575.72	58,926,004	128.56	5.6
Congo, DRC	2665.86	57,836,040	46.09	0.6
Italy	8293.68	56,528,760	146.72	4.2
Ukraine	4261.97	47,400,144	89.91	3.2
South Korea	4452.48	46,192,628	96.39	4.1
South Africa	4709.7	46,119,880	102.12	2.3
Myanmar	2576.75	42,012,896	61.33	0.9
Colombia	3325.62	41,699,424	79.75	1.3
Sudan	1823.95	40,477,688	45.06	1
Spain	7036.97	39,481,976	178.23	5.4
Argentina	4732.5	38,680,324	122.35	2.3
Poland	4242.28	38,523,048	110.12	3.3
Tanzania	1707.47	35,691,664	47.84	0.7
Kenya	2090.82	32,995,516	63.37	0.8
Canada	11294.84	32,022,750	352.71	7.6
Algeria	2489.48	31,531,672	78.95	1.6
Morocco	1862.2	31,171,148	59.74	0.9
Afghanistan	1334.04	28,403,620	46.97	0.1
Nepal	1750.11	27,308,324	64.09	0.7
Peru	1581.67	27,266,494	58.01	0.9
Uganda	1738.03	26,512,924	65.55	1.1
Uzbekistan	2219.05	26,386,720	84.10	1.8
Iraq	1785.02	25,398,480	70.28	0.9
Saudi Arabia	4057.19	25,289,332	160.43	4.6
Venezuela	3122.66	24,304,196	128.48	2.2
Malaysia	2344.2	22,441,990	104.46	2.2
Romania	2146.16	22,365,804	95.96	2.4
North Korea	1047.27	22,079,722	47.43	1.4
Ghana	1373.14	20,753,768	66.16	1
Yemen	1343.43	19,757,588	68.00	0.8
Sri Lanka	1547.01	19,600,378	78.93	1
Australia	2672.72	19,312,536	138.39	6.6
Mozambique	704.74	18,906,650	37.27	0.6

(*Continued*)

Table 1 *Continued*

Country	ISA (km^2)	Population 2004 (LandScan)	ISA/person (m^2)	GHA/person (Global Footprint Network)
Syria	1537.85	17,789,538	86.45	1.7
Madagascar	865.25	17,362,132	49.84	0.7
Cote d'Ivory	994.88	16,300,517	61.03	0.7
Netherlands	1985.17	16,115,017	123.19	4.4
Cameroon	764.88	15,955,608	47.94	0.8
Chile	1427.71	15,293,033	93.36	2.3
Kazakhstan	1153.13	15,185,784	75.93	4
Guatemala	1135.63	14,271,432	79.57	1.3
Burkina Faso	681.53	13,547,507	50.31	1
Cambodia	857.19	13,373,515	64.10	0.7
Ecuador	1132.39	12,774,985	88.64	1.5
Zimbabwe	679.03	12,654,464	53.66	0.9
Mali	399.48	11,991,301	33.31	0.8
Malawi	809.38	11,916,622	67.92	0.6
Niger	412.45	11,366,923	36.29	1.1
Cuba	851.36	11,147,445	76.37	1.5
Zambia	495.12	11,123,909	44.51	0.6
Angola	373.3	10,940,268	34.12	1
Senegal	563.97	10,813,660	52.15	1.2
Serbia & Montenegro	1066.04	10,795,336	98.75	2.3
Belgium	1669.93	10,370,094	161.03	5.6
Belarus	805.16	10,320,822	78.01	3.3
Portugal	1646.52	10,294,616	159.94	4.2
Czech Republic	1439.44	10,232,928	140.67	4.9
Greece	1543.49	10,090,290	152.97	5
Hungary	1262.13	10,033,943	125.79	3.5
Chad	271.15	9,658,690	28.07	1
Tunisia	995.95	9,637,170	103.34	1.5
Guinea	365.58	8,928,017	40.95	0.9
Bolivia	617.87	8,744,160	70.66	1.3
Sweden	1892.6	8,698,591	217.58	6.1
Dominican Republic	671.29	8,696,206	77.19	1.6
Rwanda	579.53	8,249,077	70.25	0.7
Austria	1095.89	8,136,709	134.68	4.9
Somalia	201.89	8,081,546	24.98	0.4
Azerbaijan	587.02	7,868,001	74.61	1.7
Switzerland	861.64	7,488,580	115.06	5.1
Bulgaria	792.96	7,457,232	106.33	3.1
Benin	413.35	7,295,320	56.66	0.8

(*Continued*)

Table 1 *Continued*

Country	ISA (km^2)	Population 2004 (LandScan)	ISA/person (m^2)	GHA/person (Global Footprint Network)
Haiti	457.01	7,290,397	62.69	0.6
Tajikistan	498.16	7,009,976	71.06	0.6
Honduras	514.76	6,695,838	76.88	1.3
El Salvador	553.56	6,548,425	84.53	1.4
Burundi	456.2	6,365,889	71.66	0.7
Paraguay	532.23	6,183,984	86.07	4.2
Laos	352.57	6,051,414	58.26	0.9
Israel	1066.54	5,981,165	178.32	4.6
Sierra Leone	275.81	5,799,592	47.56	0.7
Jordan	514	5,590,674	91.94	1.8
Libya	726.81	5,565,879	130.58	3.4
Togo	313.72	5,501,776	57.02	0.7
Slovakia	726.05	5,443,080	133.39	3.2
Nicaragua	374.27	5,317,195	70.39	1.2
Denmark	586.24	5,150,440	113.82	5.8
Finland	1647.19	5,104,438	322.70	7.6
Kyrgyzstan	377.52	5,078,002	74.34	1.3
Papua New Guinea	272.48	5,009,798	54.39	2.4
Turkmenistan	466.83	4,906,458	95.15	3.5
Georgia	267.17	4,615,496	57.89	0.8
Moldova	302.07	4,422,554	68.30	1.3
Eritrea	219.44	4,398,847	49.89	0.7
Croatia	572.24	4,317,700	132.53	2.9
Norway	984.95	4,193,063	234.90	5.8
Singapore	344.98	4,048,821	85.21	
Bosnia & Herzegovina	390.55	3,986,004	97.98	2.3
Costa Rica	437.08	3,941,372	110.90	2
Ireland	626.38	3,835,449	163.31	5
Puerto Rico	661.28	3,773,716	175.23	
Central African Republic	116.06	3,741,735	31.02	0.9
New Zealand	483.68	3,706,823	130.48	5.9
Lithuania	264.03	3,621,447	72.91	4.4
Albania	226.79	3,433,460	66.05	1.4
Uruguay	387.18	3,387,667	114.29	1.9
Lebanon	406.8	3,357,712	121.15	2.9
Liberia	158.4	3,283,682	48.24	0.7
Congo	150.9	3,044,534	49.56	0.6
Armenia	187.27	2,995,554	62.52	1.1
Mauritania	84.18	2,983,239	28.22	1.3

(Continued)

Table 1 *Continued*

Country	ISA (km^2)	Population 2004 (LandScan)	ISA/person (m^2)	GHA/person (Global Footprint Network)
Panama	271.75	2,947,029	92.21	1.9
Mongolia	111.03	2,750,701	40.36	3.1
Oman	439.31	2,736,018	160.57	
Jamaica	280.99	2,592,049	108.40	1.7
West Bank	274.76	2,378,777	115.50	
United Arab Emirates	891.09	2,346,994	379.67	11.9
Latvia	180.15	2,222,662	81.05	2.6
Bhutan	120.01	2,074,466	57.85	
Macedonia	229.38	2,042,531	112.30	2.3
Slovenia	299.05	2,015,099	148.40	3.4
Namibia	130.02	1,953,648	66.55	1.1
Kuwait	357.62	1,889,240	189.29	7.3
Lesotho	90.39	1,849,032	48.89	0.8
Botswana	110.07	1,644,651	66.93	1.6
The Gambia	89.74	1,507,842	59.52	1.4
Guinea-Bissau	61.6	1,368,481	45.01	0.7
Estonia	177.79	1,307,963	135.93	6.5
Gabon	77.84	1,298,646	59.94	1.4
Gaza Strip	68.96	1,209,006	57.04	
Mauritius	113.06	1,200,550	94.17	1.9
Swaziland	93.61	1,162,124	80.55	1.1
Timor Leste	64.49	1,003,994	64.23	
Trinidad & Tobago	142.11	948,768	149.78	3.1
Qatar	249.43	802,036	311.00	
Fiji	63.07	775,863	81.29	
Cyprus	156.97	742,950	211.28	
Reunion	72.19	734,020	98.35	
Guyana	52.67	715,710	73.59	
Comoros	39.72	582,472	68.19	
Bahrain	138.46	570,062	242.89	
Luxembourg	79.8	462,461	172.56	5.6
Suriname	48.82	435,662	112.06	
Equatorial Guinea	19.13	421,533	45.38	
Martinique	55.27	413,113	133.79	
Guadeloupe	54.08	387,869	139.43	
Cape Verde	32.22	374,931	85.94	
Malta	48.56	366,060	132.66	
Brunei	70.52	290,885	242.43	
Solomon Is.	11.39	281,828	40.41	

(*Continued*)

Table 1 *Continued*

Country	ISA (km^2)	Population 2004 (LandScan)	ISA/person (m^2)	GHA/person (Global Footprint Network)
Belize	30.36	270,064	112.42	
The Bahamas	40.21	269,490	149.21	
Barbados	32.4	258,078	125.54	
Western Sahara	19.83	256,089	77.43	
Iceland	35.52	237,436	149.60	5
Djibouti	11.42	188,722	60.51	
New Caledonia	22.44	184,678	121.51	
French Polynesia	18.56	175,349	105.85	
Netherlands Antilles	30.18	172,813	174.64	
Sao Tome & Principe	11.95	167,632	71.29	
Mayotte	14.83	166,945	88.83	
St Lucia	15.45	158,436	97.52	
French Guiana	18.48	154,178	119.86	
Guam	35.61	154,144	231.02	
Vanuatu	9.73	146,203	66.55	
Samoa	9.21	144,839	63.59	
Virgin Is.	19.84	98,550	201.32	
Jersey	8.62	88,537	97.36	
St Vincent & the Grenadines	7.05	79,364	88.83	
Grenada	8.21	75,057	109.38	
Aruba	17.18	70,931	242.21	
Andorra	14.58	69,968	208.38	
Northern Mariana Is.	8.65	69,724	124.06	
Isle of Man	7.74	68,773	112.54	
Seychelles	6.92	68,730	100.68	
Antigua & Barbuda	9.47	63,737	148.58	
Guernsey	4.8	56,507	84.95	
American Samoa	6.66	50,609	131.60	
Monaco	3.89	44,494	87.43	
Dominica	6.36	43,562	146.00	
Faroe Is.	3.07	38,011	80.77	
Micronesia	2.68	35,465	75.57	
Greenland	1.1	34,715	31.69	
Liechtenstein	6.45	33,910	190.21	
St Kitts & Nevis	3.51	28,532	123.02	
San Marino	5.96	25,015	238.26	
Cayman Is.	5.92	24,541	241.23	
British Virgin Is.	2.74	18,258	150.07	

(*Continued*)

Table 1 *Continued*

Country	ISA (km^2)	Population 2004 (LandScan)	ISA/person (m^2)	GHA/person (Global Footprint Network)
Palau	1.93	14,443	133.63	
Anguilla	1.92	12,642	151.87	
Cook Is.	1.46	12,506	116.74	
Bermuda	2.04	10,164	200.71	
Turks & Caicos Is.	0.94	8,905	105.56	
Montserrat	0.75	7,442	100.78	
Nauru	0.8	6,168	129.70	
St Pierre & Miquelon	0.86	6,157	139.68	
Vatican City	0.82	6,056	135.40	
St Helena	0.61	5,930	102.87	
Falkland Is.	0.24	3,166	75.81	
Kiribati	0.12	2,348	51.11	
Gibraltar	2.08	2,134	974.70	
Niue	0.19	1,989	95.53	
Norfolk I.	0.31	1,166	265.87	
Christmas I.	0.15	390	384.62	
Marshall Is.	0.01	330	30.30	
Cocos Is.	0.01	290	34.48	
Maldives	0.03	286	104.90	
Tuvalu	0.2	153	1307.19	

(3) Exploring and evaluating the subnational estimation of ecological footprints working from the highly refined national level estimates and the disaggregated constructed area/person grid.

III Discussion

Human actions are now recognized as a significant force of environmental change at local, regional, and global scales (Turner *et. al.*, 1990). These changes have manifested as the human population has grown in number and developed in technology. This human-environment-sustainability problematic has generated numerous jeremiads (Kates, 1995). These jeremiads vary in nature from warnings about the loss of biodiversity (Wilson, 1992) to shortages of food and water (Malthus, 1798; Postel, 1997), the dwindling of energy supplies (Hubbert, 1956), and the damaging effects of climate change (Mastrandrea and Schneider, 2005).

Despite the wide-ranging nature of warnings regarding the sustainability of human civilization today, a common neo-Malthusian thread pervades many if not most of these jeremiads. A widely used characterization of this neo-Malthusian thread is the $I = P \times A \times T$ equation describing human **I**mpact as the product of **P**opulation times **A**ffluence times **T**echnology (Ehrlich and Holdren, 1971). This equation appeals to many because it recognizes that both population and consumption contribute to environmental impact. Unfortunately the role of technology is very difficult to quantify and it has been suggested that the T (technology variable) become a more complex factor called CITE (the '**C**ulture, **I**nstitutions, and **T**echnology **E**ffect'; Holdren, 1991). This research explores the idea of using a very simple proxy for the I = P × A × T equation: pavement (eg, constructed area or impervious surface). We believe pavement is a promising spatially explicit proxy measure of human impact on the environment because it captures many of these confounds and complexities associated with the 'teasing apart' of problems associated with the separation of production and consumption in the world today (Brewer and Trentmann, 2006). We derive our measure of constructed area from a simple regression using nighttime satellite imagery and population count. This global representation of impervious surface can be used as a proxy measure of many human impact related variables such as energy consumption, urbanization, economic activity, and CO_2 emissions.

The threats of climate change as driven by increases in the concentration of greenhouse gases such as CO_2 seem to be increasingly recognized as significant and real. Al Gore's highly publicized narration of the movie 'An inconvenient truth' and the Stern report of 2007 (Stern, 2007) are seen by many as a 'tipping point' in overall public conviction as to the reality and seriousness of the problems associated with climate change. It is interesting and perhaps surprising to note that simple measurements of an extremely basic component of the atmosphere (CO_2) (Keeling *et al*., 1995) have most likely triggered more public awareness and acceptance of deleterious human impact on the Earth than the combined lamentations of prominent neo-Malthusian scholars such as Garret Hardin, Paul Ehrlich, and Jared Diamond (Hardin, 1968; Ehrlich and Ehrlich, 1990; Diamond, 2005).

The now famous 'Keeling Curve' charting atmospheric CO_2 concentrations over Mauna Loa in Hawaii over time (Keeling *et al*., 2004) is an interesting and poignant globally aggregate measure of anthropogenic impact on the planet. In many respects Keeling's curve is like a planetary 'idiot light' on the dashboard of a car telling humanity that something might be wrong. And, like the 'idiot light' on the dashboard of a car, the 'Keeling Curve' only provides a limited amount of information as to what the exact nature of the problem is and how it can be addressed. Nonetheless, 'idiot lights' are invaluable devices if they trigger the following three responses: (1) stop behaviour that has serious potential negative consequences (ie, continuing to drive a car with an overheating engine or allowing atmospheric CO_2 concentrations to double); (2) diagnose what caused the 'idiot light' to turn on; and (3) treat the cause (eg, putting oil in the engine, coolant in the radiator, shifting to renewable energy supplies, etc). The seemingly endless debates about the reality of global warming seem to be waning at this point which suggests that these three steps might be taken more vigorously in the near future. However, new and more difficult questions arise when it is necessary to decide which and whose behaviour must change and how we hope to bring about those changes.

The analogy between the 'Keeling Curve' and an 'idiot light' may hold some validity; however, the subsequent information needed to make diagnoses and change behaviour is more complicated than simply 'looking under the hood'. Fortunately, there is an abundant amount of information in the form of remotely sensed satellite imagery that can inform our understanding of the human-environment-sustainability problematic. In contrast to the globally aggregate measure that the CO_2 data at Mauna Loa provides, remotely sensed images of the Earth provide spatially explicit data that can be used as inputs for a suite of methods and analyses that enable more accurate measurement, mapping, and monitoring of human impacts on the Earth.

IV Conclusion

The 2007 National Research Council report *Earth science and applications from space: national imperatives for the next decade and beyond* (NRC, 2007) specifically identifies the requirement for measuring the 'human footprint' on ecological systems. Below is a quote from the report.

> **Observations of Human Impacts**
>
> Human influences on the Earth are apparent on all spatial and temporal scales. Thus, an effective Earth information system requires an enhanced focus on observing and understanding the impact of humans, the influence and evolution of the built environment, and the study of demographic and economic issues. For instance, space-derived information on urban areas can provide a platform for fruitful interdisciplinary collaboration among Earth scientists, social scientists (e.g. urban planners, demographers, and economic geographers), and other users in the applications community. Data on the geographic 'footprint' of urban settlements, identification of intra-urban land-use classes, and changes in these characteristics over time are required to facilitate the study of urban population dynamics and composition, and thereby to improve the representation of human-modified landscapes in physical and ecological process models. Because of the rapid growth in urban areas, particularly in the developing world where there are few alternative sources of information on urban extent and land cover, these observations are needed to understand a growing source of anthropogenic forces on regional weather and climate, air and water quality, and ecosystems, and to apply this understanding to protect society and manage natural resources.
>
> *Recommendation*: Earth system observations should be accompanied by a complementary system of observations of human activities and their effects on Earth.'
> (NRC, 2007)

Human impacts on ecosystems are myriad in nature and magnitude. This study makes no claims on characterizing the nature and magnitude of these myriad impacts individually; however, it does provide a proxy measure of the magnitude of aggregate human impact for the entire planet at 1 km^2 spatial resolution. The correlation between the relatively sophisticated Ecological Footprint indices and the relatively simple constructed area per person estimates derived from satellite imagery strongly suggest that satellite products constitute a very profound and simple measure of human impacts on terrestrial ecosystems that can be updated and tracked over time.

During the environmental movement of the 1970s the concept of $I = P \times A \times T$ emerged as an equation for describing human impacts on the environment (Holdren and Ehrlich, 1974; Holdren, 1991). Much of global change research conducted with satellite imagery focuses on the detection and quantification of the I term in this equation. Our research has demonstrated the viability of a satellite based index that serves as a proxy measure of $P \times A \times T$. We use this index to estimate impact in the form of a 'human ecological footprint' that acknowledges that impacts are widely distributed across the Earth (eg, there is a complex separation of production and consumption). This measure of 'impact' is spatially explicit, derived uniformly across the globe, and strongly correlates with measures of 'ecological footprints' that are derived from a much more complex set of measurements.

Note

1. The global density grid of constructed surfaces and spreadsheet summaries of the results are available at http://www.ngdc.noaa.gov/dmsp/download_global_isa.html (last accessed 13 August 2009).

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