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GSA Supplemental Data Repository Material

Data Repository material for **Land transformation by humans: A review**
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Contents:

A. Abbreviations used

FAO	Food and Agriculture Organization of the United Nations
KG'01	Klein Goldewijk (2001) and Klein Goldewijk (writ comm., March 2010).
KG'11	Klein Goldewijk et al. (2011)
P+	Pongratz et al. (2008a, 2008b) and Pongratz (writ. comm., January 2012)
RF	Ramankutty and Foley (1999)
R+	Ramankutty et al. (2008)

B. Definitions of terms

The definitions of cropland, pasture, and forest used by RF and KG follow those established by the FAO (2010). Briefly, c*ropland* includes market and kitchen gardens as well as farms, and also includes fallow land that will be planted in the future. *Pasture* is land used to grow forage crops, either cultivated or growing wild. Some studies include semiarid land and grassy woodland. *Forested* land is that with more than 10% crown cover. Interpretation of satellite and other data in terms of these definitions commonly differs among investigators, however.

C. Data sources used in constructing Figure 2

The FAO data begin in 1961. They are based on reports from statistical units of the individual countries and are carefully checked by the United Nations Statistical Division. These data are collected for governmental and *not* scientific purposes, and therefore have shortcomings (see Grainger, 2010, and references therein for problems with forest areas); however, they are the best available and are also sufficient for our purposes. KG'11 (p. 80) note that they are "regarded as authoritative but still disputed for some countries."

RF used FAO data and satellite imagery calibrated with extensive ground-based observations to estimate the land area under forest and that devoted to agricultural crops. To project their data backwards to 1700 AD, they used an extensive compilation of historical cropland inventory. KG'01 developed a database (the HYDE database) founded primarily on FAO data. He estimated the area of pasture in addition to that of cropland and forest. He then used historical population data and country-specific per capita land use estimates to hindcast global percentages to 1700. Because he used the FAO data as a starting point, the KG'01 and FAO data sets agree where they overlap. The RF and KG'01 estimates of forest cover generally agree well (Fig. S1A). However, RF's values for cropland were consistently higher than those of KG'01 (Fig. S1A) (e.g. 17.9 vs. 15.2 Mkm^2 in 1990). Klein Goldewijk and Ramankutty (2004, p. 339) attribute this to use of satellite data by RF.

The estimates of cropland and pasture in both these early studies have now been updated. R+ used two satellite imagery datasets rather than only one, and they use data from nearly 16,000 local, state, or national administrative units for calibration. They do not provide an estimate for forest, and have not yet projected their estimates backward. Their estimates are for 2000 A.D. KG'11 included more recent FAO data and also took into consideration likely changes in per capita values for cropland and pasture. The R+ and KG'11 values for cropland now agree well (Fig. S1A) ($15^{+2.8}_{-2.1}$ and 15.3 Mkm^2, respectively). However, their pasture estimates (28 and 34.3 Mkm^2, respectively) do not. This is likely because R+ do not include semiarid land and grassy woodland as pasture.

Another recent study (P+) obtained somewhat different estimates. They start with the RF and KG'01 data sets and update some of the data on population and historical cropland patterns. They also allowed for expansion of cropland into land previously used as pasture. They project their estimates both backward and forward using population data (Fig. S1A). The P+ and RF values for cropland agree well, but fall above the updated R+ value for 2000.

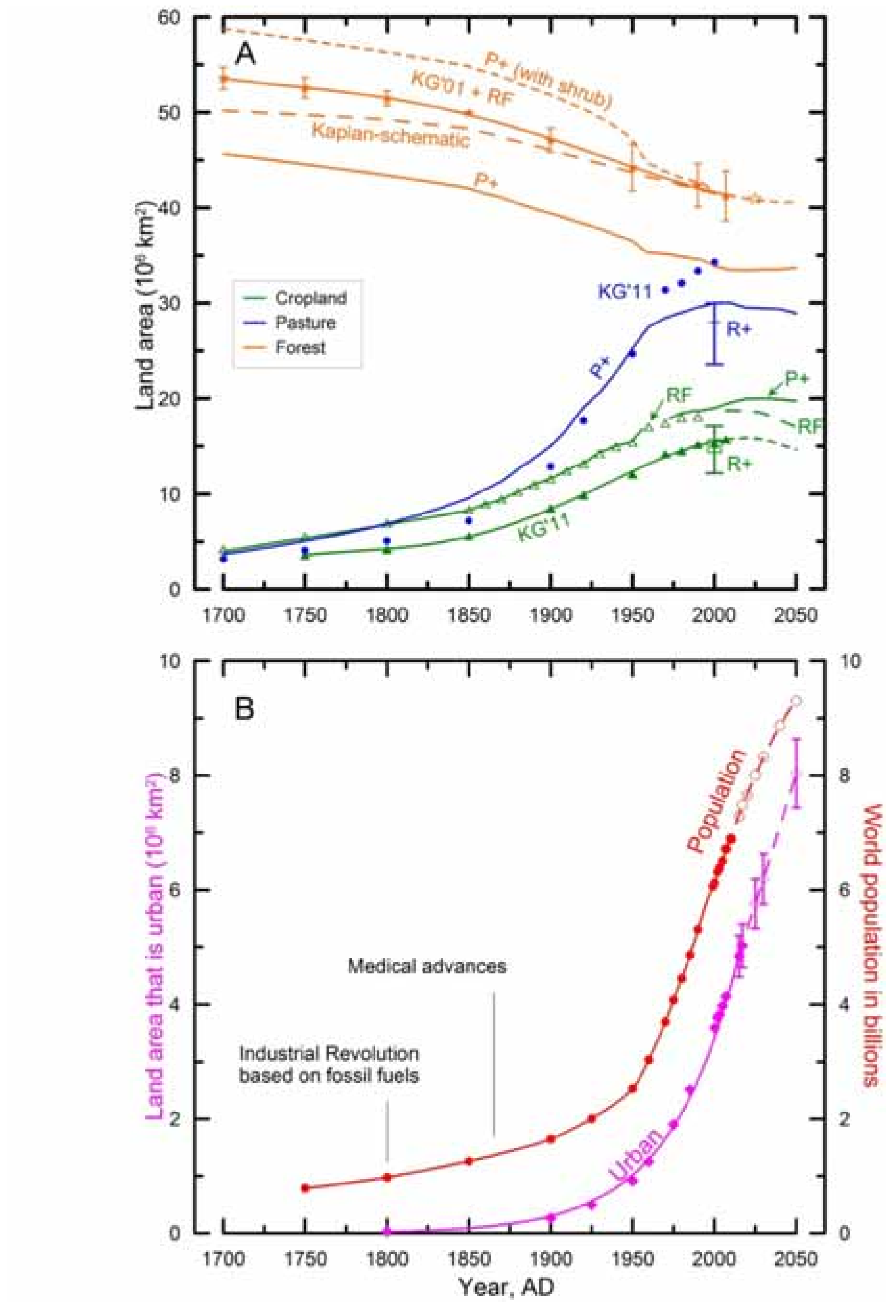

Figure S1. **A**. Changes in land use through time, with extrapolations to 2050 AD. Forest data include planted forests. The points and line labeled KG'01 + RF are means and standard deviations of the RF and KG'01 estimates for Forest. **B**. Changes in Urban land and in population through time. Uncertainties in the former are based on an uncertainty of ±100 in the population density. Meyer and Turner (1992) provide an extended discussion of uncertainties in data such as these and the other data in Table 1 of the published paper.

The RF and KG'01 estimates of forested area agree well and have not been updated. P+'s estimates for forest are systematically ~15% lower (Fig. S1A). On the other hand, if we include in "forest" P+'s estimate of shrublands, the values agree with RF and KG'01 for the past 50 years. Prior to ~1960, however they are ~10% higher (Fig. S1A). The reason for these differences likely involves the definition of "forest."

Kaplan et al. (2009) noted that the agricultural area used to support a given number of people has decreased though time, owing to technological improvements that allowed more intensive farming. A rigorous calculation of this effect requires detailed data on the land area occupied by different population densities in the past. In Figure S1A we show the effect schematically.

We needed estimates of the urban population at various times in order to hindcast the urban area. Data spanning 1900 to 2007, and projected to 2050, are available from the United Nations (UNPD 2004, Tables 1, 2, & 6, 2007a, 2007b), as is an estimate of the mean urban population density: 902 people/km^2 (UNPD, 2007a). Another population density estimate of 796 people/km^2 can be obtained from the CIESIN (2010) data for 2005. We used the latter value. Dividing the urban population by a density yields an estimate of the urban area (Fig. S1B). The estimate for 1800 was obtained similarly using an urban population estimate from Kelley and Williamson (1984). Uncertainties shown are based on an uncertainty of ±100 in the population density, and do not take into account the uncertainty in the actual populations, as these are not given in the sources referenced.

D. Estimating area modified by deposition of soil eroded from agricultural land

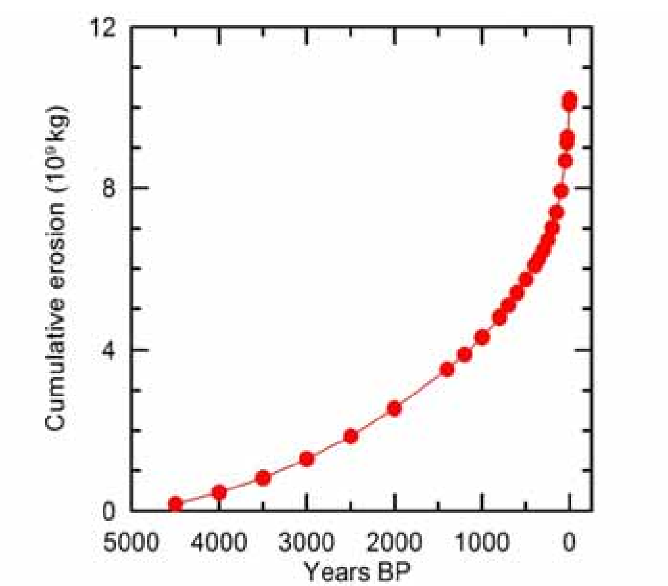

Figure S2. Estimated cumulative erosion since 5000 BP.

As described in the paper, we used erosion rates of 15 and 5 t ha^{-1}y^{-1} for cropland and pasture, respectively, and assumed that 70 ± 10% is redeposited on slopes and floodplains a short distance from its source. We assumed that 0.25 ha of cropland and 0.75 ha of pasture were required to feed a person in the middle Holocene (D. Pimentel, written communication, 1999). We used population estimates from Thomlinson (1976) (See Hooke, 2000, Fig. 3) and the percentage of the population dependent on agriculture from Hooke (2000), numerically integrating to estimate the total amount of sediment eroded from cropland and pasture in the past 5000 years (Fig. S2). The mean thickness deposited likely increased through time. We assumed that it was now ~1 ± 0.5 m. Using a density of 1360 kg m^{-3} we obtained an area. Because the required *per capita* area of pasture is three times that of cropland, while erosion rates from the latter are three times those from the former, our estimates of the land area modified by sediment eroded from cropland equals that from pasture, both being 2.63 ± 1.43 Mkm^2, giving a total of 5.26 ± 2.03 Mkm^2. The uncertainty is based on uncertainties of 15% in the deposition density, 25% in population dependent on agriculture, in area of crop or pasture land required per capita, and in erosion rates, and 50% in thickness deposited. (Extending the calculation back to 10,000 BP raises the total to 5.55 ± 2.14 Mkm^2.)

E. Estimating the land area disturbed by logging

To estimate the area impacted by logging, we first obtained the annual production, P_i (m^3y^{-1}), of roundwood (= saw logs, pulpwood, woodfuel, etc.) for 1998 – 2007 from FAOSTAT (http://faostat.fao.org/DesktopDefault.aspx?PageID=626&lang=en#ancor) (Table S1). The subscript is the year, with i = 1 corresponding to 2007, i = 2 to 2006, and so forth. We found several estimates of the yield of roundwood per hectare, Y, ranging from 2 to 30 $m^3ha^{-1}y^{-1}$ (Table S2). Influenced, particularly, by the value in row 5 of the table, we used 15 ± 5 $m^3ha^{-1}y^{-1}$. We assumed that half (=F) of the area logged in 2007 was disturbed, and that regrowth healed 50% (=R) of the land each year, so that in 2007, the land area remaining disturbed from the 2006 cutting would be 50% of that disturbed in 2006, that remaining disturbed from the 2005 cutting would be 25% of that disturbed in 2005, and so forth. Thus, in 2007 the area remaining disturbed, A_{logged}, is: $A_{\text{logged}} = \frac{F}{Y}\sum_{i=1}^{n} P_i R^{n-1}$. The uncertainty is based on an uncertainty of 50% in R and 25% in F.

The area disturbed depends, in part, on the harvesting method used (Wang et al., 2005). Harvesting commercially valuable tree species with intensive techniques (clearcuting) results in more damage to the soil than techniques typically used by light selective logging (Fredericksen and Putz, 2003). However, the latter require more roads and this increases the severity of localized soil disturbance (see http://maineforestry.net/Forestry%20Items/

timber_hvt_methods.htm). The secondary impacts of these roads are commonly more serious than the logging itself, as they facilitate subsequent land transformation. We did not try to take this difference in harvesting technique into account.

Table S1. Worldwide production of roundwood (from FAOSTAT)

Year	2007	2006	2005	2004	2003	2002	2001	2000	1999	1998
Mm^3	3549	3530	3571	3506	3449	3395	3336	3425	3353	3295

Table S2: Roundwood production per hectare

Row	Production, $m^3ha^{-1}y^{-1}$	Reference / source	Comments
1	20.4	Cubagge et al. (2007), p. 242	An average for 20 species in 5 countries (Argentina, Brazil, Chile, Uruguay and US). These are some of the most important areas for wood production in the world. This is an analysis from FAO data of 2005
2	17.9	Sedjo (1983) *in* Cubagge et al. (2007), p. 240	7 representative species on 4 contin-ents
3	21.4	Tomberlin and Buongiorno (2001) *in* Cubagge et al. (2007), p. 240	
4	15-30 2-5	http://www.fao.org/docrep/c3848e/c3848e04.htm	Quoting from the website, "*In tropical regions … the mean annual increment of coniferous plantations ranges from 15 to 30 $m^3ha^{-1}y^{-1}$, compared with only 2 to 5 $m^3ha^{-1}y^{-1}$ in temperate zones. The pattern for broad-leaved species is similar.*"
5	14.2	http://www.fao.org/forestry/8949-035048d436d27054de59765e336c75826.pdf	An average of 151 species for 30 coun-tries all over the world
6	13.6	http://www.forestry.co.za/statistical-data/	An average for the period 1998-2007 for South Africa

F. Estimating the land area modified by roads in rural areas

As noted in the published paper, we used data on the total lengths of roads in 188 countries (IRF-WRS, 2009). In 121 of these, the data are broken down by road class – motorways, national roads, regional roads, and other roads. Based on data on the standard widths of highways in the US, including shoulders, and disturbed areas beyond shoulders (Anonymous, 2007), and on our own observations, we assumed mean widths for these road classes of 60, 35, 30, and 10 m, respectively. For the remaining countries we used a mean of 30 m. The total disturbed area thus obtained was 0.58 Mkm^2. The IRF-WRS data include all roads, whereas we are interested only in roads in rural areas. By comparing data on lengths of roads in rural areas in the United States (Federal Highway Administration, 2008); Latvia (Teibe, 2004); India, The Philippines, Sri Lanka, and Thailand (Metschies, 2002); and India (Sarkar, 2007) with the IRF-WRS data for those countries, we found that 70 ± 5% of the roads were in rural areas. The rest are in urban settings and thus are included in urban area. Assuming an uncertainty of ±15% in road widths and in the percentage of rural roads, we obtain 0.4 ± 0.1 Mkm^2.

Note that roads in rural areas include motorways and interstate highways, not just rural roads.

G. Calculations and data sources for mining

Our data on the area disturbed by *Mining* are shown in Table S3. These regions represent 22% of Earth's ice-free land area. Data like this are difficult to find. Using satellite imagery or other data to locate and measure the area of every visible mine, country-by-country, was beyond the scope of the present study.

Table S3: Land area disturbed by mining

Country / *State or Region*	Area of region, km^2	Area disturbed by mining, km^2	Area disturbed as % of total[a]	Reference / Year to which estimate applies (by extrapolation in some cases)
United States	9,826,630	32,600	0.33[b]	(SCS, 1977) / 2008
China	9,596,960	~26,000	0.27[c]	(Guo et al., 1989) / 2008
India	3,287,590	~8,000	0.24	(Singh, 2007) / 2007
Australia				
Western Australia	2,529,875	1,620	0.06	(ACRC, 2008, p. 5) / 2008
Queensland	1,730,648	1,170	0.07	(Queensland Gov't, 2003) / 2003
Peru	1,280,000	7,140	0.56	(MEMP, 2008) / 2008
Sweden	441,370	220	0.05	(Neeb, 2004) / 2003
Ecuador	283,561	650	0.23[d]	(Sandoval, 2002 / 2001)
United Kingdom	242,900	2,190	0.90	(Bloodworth et al., 2009) / 2000
Guatemala	108,889	5	0.005	(MEM, 2004) / 2004
Spain				
Catalonia	31,895	~147	0.46	(Departament de Medi Ambient, 2010 / 2010)
Valencia Region	23,305	58	0.25[e]	(El País, 2004) / 2004
Basque Country	7,234	17	0.24	(Neiker Tecnalia-IVIDA, 2005)/2005
Colombia				
Capital District	1,622	2	0.14	(Arjona, 2009 / 2007)
TOTALS	29,392,500	79,895	0.27	

[a] Some areas in Column 3 have been rounded but percentages in Column 4 have been calculated based on the original areas.

[b] The estimate for the United State uses data from 1930, 1964, 1971, 1974, and 1977 from the USDA Soil Conservation Service (SCS, 1977) and a linear extrapolation to 2008.

[c] Guo et al. (1989) estimate that 20,000 km^2 of land were disturbed by mining in China in 1989, and that the land disturbed was then increasing at a rate of 2000 km^2 y^{-1}, and that by the end of the century it would be increasing at a rate of 3300 km^2y^{-1}. By assuming that this increase would be linear, we estimated that by 2008 the land area disturbed would be 26,045 km^2. Other estimates (Hossner and Shahandeh, 2002; Ye et al., 2000) ultimately refer back to Guo et al. (1989).

[d] Mining areas authorized for exploitation in March 2001. This is probably a maximum value, as not all of the area would have been disturbed in 2001.

[e] This disturbed area increased 50 % between 1990 and 2002.

H. Additional supporting references

In this section we cite some supporting references for which there was not enough space in the published text. Headings in blue correspond to those in the published paper.

INTRODUCTION

Numerous papers in the late 1990s and the first decade of the present century drew attention to a global decline in biodiversity (e.g. Butchart et al., 2007) and to the impacts of land-use changes on local climate (Snyder et al., 2004), on biodiversity, on ecosystem services, and on soil degradation (See also Lambin and Geist, 2006, p. 1 for references).

LAND AREA MODIFIED BY HUMAN ACTION

Ehrlich and Ehrlich (1981, p. 149-151) provide an extended discussion of environmental problems arising from pollution.

The effect of pollution on pollinators, predators and plant growth, and hence on agricultural productivity, is discussed further by Krupa et al. (2001). See Burke et al. (2006) for more on the effect of climate change on productivity.

Land modified by human action as of 2007

Reservoir construction modifies the landscape both by forming artificial lakes and by altering tributary rivers, the shoreline and submerged topography (Nilsson et al., 2005).

DISCUSSION

Canadell et al. (2007) is another reference that discusses land use change from an ecological perspective.

Cropland

1. *Increase in urban area at the expense of agricultural land*: In the EU, over 900 km^2 of agricultural land were converted to urban use *annually* during the 1990s (EEA,

2005, p. 309). In a region of China urban area increased 346%, mostly at the expense of agricultural land, between 1988 and 1996 (Seto et al., 2002).

3. *Deterioration of agricultural land*: Myers (1992) estimated that nearly 0.3 Mkm^2 of farm land becomes non-productive *annually* due to soil degradation.

PROGNOSIS FOR THE FUTURE

Concern for the World population increase is not new. In the late 1960s the UN recognized that population growth was detrimental to environmental quality (WPM, 2001, p. 3). In the early 1970s, the Ehrlichs (1972), among others, argued that Earth was already overpopulated.

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