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Reconsidering the Limits to World Population: Meta-analysis and Meta-prediction

JEROEN C. J. M. VAN DEN BERGH AND PIET RIETVELD

We performed a meta-analysis on the basis of 69 past studies that have assessed a limit to the world population. The estimates of this limit range from 0.5 billion to 1×10^{21} billion people. A meta-analysis allows us to see what overall picture emerges when different methods, limiting factors, levels of aggregation, and data are taken into account. Limiting factors for the world population include water availability, energy, carbon, forest products, nonrenewable resources, heat removal, photosynthetic capacity, and the availability of land for food production. Methods employed in the population studies include spatial extrapolation, modeling of multiple regions, temporal extrapolation, actual supply of a resource, hypothetical modeling, and dynamic systems modeling. Many studies rely on important assumptions about the level of technology, the energy intake per person, and the available arable land. The meta-analysis employs both descriptive statistics and regression analysis. We used the findings of these analyses to propose a number of meta-estimates of limits to world population. When taking all studies into account, the best point estimate is 7.7 billion people; the lower and upper bounds, given current technology, are 0.65 billion and 98 billion people, respectively. We offer a range of other conditional estimates as well. An important conclusion of this study is that recent predictions of stabilized world population levels for 2050 exceed several of our meta-estimates of a world population limit.

Keywords: carrying capacity, meta-analysis, population limit, quantitative studies, world population

Can human population growth go on indefinitely? Many natural and social scientists believe the answer is a definite no, and many have tried to assess a hard limit for world population. The concepts used in estimating such a limit include optimum population, carrying capacity, and limits to growth. These concepts reflect, first of all, the consideration that individual human beings need minimum amounts of certain natural resources—notably land, fresh water, energy, and material resources (biotic and abiotic)—to live a good life in terms of eating, drinking, consuming goods and services, and using space. In addition, they take into account the problem that necessary resources are finite in supply. The two elements taken together suggest that there may be an upper bound—effective or not—to the size of the human population. The purpose of this article is to examine what all past studies on global population limits, taken together, have to say, taking notice of both differences and similarities among studies.

Whereas earlier syntheses have been restricted to qualitative analysis (Boerman 1940, Cohen 1995), this study goes one step further by undertaking a quantitative meta-analysis based on descriptive statistics and multiple regression analysis. The idea behind meta-analysis is simple—namely, that the marginal value of an additional primary study is quite low when a large number of primary studies are already available.

Unlike a primary study, a meta-analysis that takes variation in study characteristics into account can provide insight about which factors have been critical influences on earlier results. This, in turn, leads to better overall understanding and prediction (e.g., Cooper and Hedges 1994).

Meta-analysis is particularly relevant for synthesizing the results of earlier studies on global population limits. The main reason is that most of these studies use a quantitative approach to assess a limit, which allows researchers to systematically trace differences and similarities among studies and record them using quantitative indicators. The oldest population study available, performed by the prototype microbiologist Antoni van Leeuwenhoek in 1679, already used a quantitative method, even if it was a “back-of-the-envelope”

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calculation. By extrapolating the population density of the Netherlands at the time (120 people per square kilometer [km²]) to the rest of the world, Leeuwenhoek arrived at a global population limit of 13.4 billion people (Cohen 1995). Moreover, irrespective of the time period covered, all studies deliver a directly comparable indicator, namely population size. Because population size has a unique unit (number of individuals), no standardization of its values across studies is required. The advantage of performing a meta-analysis is that, in contrast with primary studies that use one method and usually examine one or very few limiting factors, it allows researchers to ask questions about the impact of a particular method or limiting factor relative to others.

In the following sections, we discuss our data collection and database structure, interpret descriptive statistics, discuss the results of regression analyses, and offer meta-estimates of the world population limit on the basis of these statistical findings.

Database construction

The data were collected from December 2000 to June 2001. The most important source was the seminal overview by Cohen (1995) of the literature on human population growth and its carrying capacity. He reviewed 66 studies from 1694 until 1994, most of which we included in this study. In addition, we researched more recent studies through library and Internet databases.

Some studies that at first seemed relevant were not included in the analysis, for several reasons. They concerned predictions for specific years; they were based on subjective estimates (what Cohen [1995] calls “categorical assertion”) rather than on an objective and repeatable method; their method was not clearly documented; or they were themselves surveys or completely based on other studies (Wickens 1925, Boerman 1940). We also examined the “global unified metamodel of the biosphere” developed by Boumans and colleagues (2002) to determine whether it might render an additional data point. However, in no scenario did it generate a stabilized or sustainable population level that could be interpreted as a population limit.

The selection of estimates within each study followed a similar process of sifting. If, next to a real calculation, a study presented other, unclearly derived or aggregated population limits without providing a good motivation, then we omitted the latter. When a range was given, we took the arithmetic average. Only in one case (Fremlin 1964) did we use a geometric average, when the ends of the range differed by as much as a factor of 100.

This procedure ultimately gave rise to a database that included 51 studies based on clear methods. These in turn provided 94 estimates of a limit to the world population. Since some information was collected earlier from studies based on categorical assertion (18 studies, including 21 estimates), these studies were included to allow for a comparative analysis with the method-based studies. The data set contained a total of 11 variables for all selected primary studies:

1. Primary study number (a positive integer from 1 to 70).
2. Year of publication (from 1679 to 1999).
3. Type of publication (journal, book, or other).
4. Estimate of maximum population, in billions (rounding to one digit).
5. Population at date of publication, in billions (rounding to one digit).
6. Limiting factor: land/food (land use, mostly for food production), water availability, energy (includes fossil fuel and renewable sources), carbon, heat removal, primary (photosynthetic) production, forest products, nonrenewable resources, synergy of multiple factors, or limiting factor not identified.
7. Mathematical method: Includes spatial extrapolation, modeling of multiple regions, actual supply of a resource, hypothetical modeling, dynamic systems modeling, and temporal extrapolation. Table 1 lists the methods along with a short description of each one. Categorical assertion was also considered in this category, although technically it is not a method.
8. Technology, current and future (hypothetical).
9. Diet spatially homogeneous (yes or no).
10. (Arable) land availability (high or low).
11. Energy intake (need) per person (high or low).

Variables 9 through 11 relate to the limiting factor “land/food” and associated methods (spatial extrapolation and modeling of multiple regions). Variable 9 can be regarded as a methodological parameter, providing additional information about the approach followed in a study. Variables 10 and 11 are empirical parameters. Certain observations have missing values for some of these variables, which we took into account in the statistical regression analysis. The construction of these variables required a number of data transformations, which are documented below.

Variable 10, arable land availability, takes the values “high” and “low.” We made the following choices and conversions in analyzing this variable:

- We set the border between “high” and “low” at 70 million km² (range was 7.1 million to 508 million km²).
- In the study by King ([1695] 1973), 1 *Engelse* (acre) = 0.4046 hectares = 0.004046 km². The estimate of available arable land in this study is 48 billion land acres, which equals 0.004046 × 48 = 200 million km².
- In the study by Süssmilch (1741), the area of France is given as 30,000 square French miles. Because France has an area of approximately 551,000 km², this implies that 1 square French mile is about 18.37 km². The estimated available arable land in this study is 5,160,000 square French miles; 18.37 × 5,160,000 = 95 million km².
- In the study by Ballod (1912), 33 billion acres = 0.004046 × 33 = 134 million km². For an explanation of this conversion, see the note above regarding King ([1695] 1973).

Table 1. Mathematical methods used in primary studies on global population limits.

Method	Description
Spatial extrapolation	Spatial extrapolation of a (relatively high) population density in one region or country to the rest of the world, using an estimate of the total land available. This assumes that the rest of the world would reach the same population density.
Modeling of multiple regions	Dividing the world into different regions (temperate and tropical zones or rich and poor countries), using different assumptions regarding population density, agricultural productivity, primary production (photosynthesis), or diet.
Actual supply of a resource	Examining how many people can be supported given the actual supply of a natural resource (renewable or non-renewable) in the year of study and the required input per capita.
Hypothetical modeling	Modeling based on extreme assumptions, such as extremely high buildings throughout the world and diets consisting entirely of algae, or on fundamental limits, such as heat removal capacity and carbon availability on Earth.
Dynamic systems modeling	Two world models that use multiple limiting factors (pollution and resources) and thus allow for synergetic effects of these factors on population size.
Temporal extrapolation	Extrapolating a trend over time by fitting a logistic curve on past population data. The associated carrying capacity is then interpreted as the population limit. No concrete limiting factor needs to be identified.

- In the study by Spengler (1949), 4 billion acres = $0.004046 \times 4 = 16$ million km^2 .

Variable 11, energy intake (need) per person, takes the values “high” and “low.” This variable is derived from one or more of three dimensions: (1) concrete minimum energy intake (in kilocalories [kcal]), (2) maximum population density, and (3) minimum required land area per person. Because the third of these dimensions can be easily transformed into the second (a minimum land requirement per person of $1/x \text{ km}^2$ is equivalent to a maximum population density of x people per km^2), we omit further discussion of the minimum required land area per person. However, the conversion of maximum population density into concrete minimum energy intake is only possible if an assumption is made about the productivity of land. Since no complete information on land productivity was available, we coded the energy intake variable by evaluating for each dimension (concrete minimum energy intake or maximum population density) whether the value chosen by the author was relatively low or high.

The range of values in the database for concrete minimum energy intake was 1625–5000 kcal, with most observations between 2000 and 2800 kcal. The high–low threshold for concrete minimum energy intake was set at 2501 kcal. Note that 2500 is the mode and probably also the median; note also the level of 2350 kcal for basic diet as defined by the Food and Agriculture Organization and the World Health Organization (see Cohen 1995, app. 5). The levels of concrete minimum energy intake for “US and European diets” were assumed to be high, whereas those for “Asian diets” were assumed to be low. In a few cases, energy intake was formulated in kilograms of a certain crop (grain, corn, wheat); we applied the information, provided by Cohen (1995), that one gram of wheat is equivalent to about 3.5 kcal.

The range for maximum population density was 5–68,000 people per square kilometer, with most observations between 100 and 300. The high–low threshold was set at 201. We aggregated the two dimensions when a high population density was evidently equivalent with a low energy intake. Sometimes a high population density was due to high land productivity, which we took into account whenever possible.

Although it is tempting to discuss the advantages and weaknesses of the various approaches, notably the methods, in the studies we analyzed, this is more the task of a traditional review article. Instead, our objective is to adopt as objective a stance as possible, which requires judging the primary studies as input data of comparable quality that are amenable to statistical analysis. The sources included in our study sample are listed in box 1.

Descriptive statistics

Figure 1 shows the frequency distribution of estimated world population limits. This distribution can be characterized as having a very wide spread. Three studies have delivered especially high estimates of 1×10^9 billion, 4.8×10^{14} billion, and 1×10^{21} billion people. These estimates assumed, respectively, that body heat can be removed (dissipated), that all human food is based on algae production, and that all carbon on Earth is embodied in people.

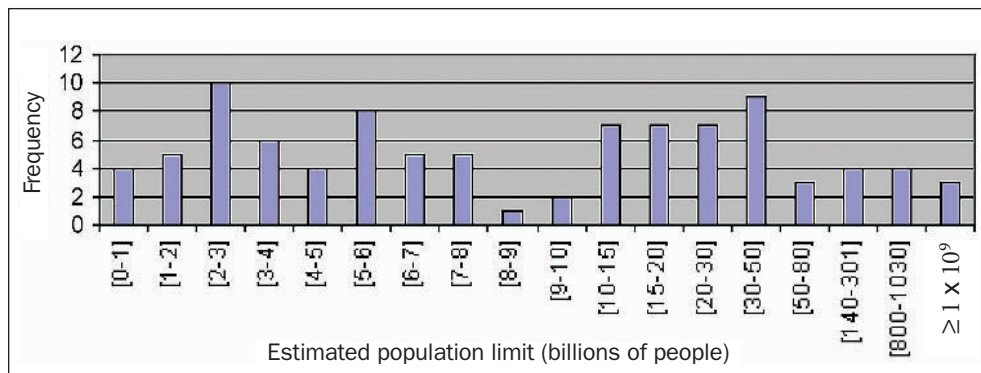


Figure 1. Frequency distribution of estimated population limits, in billions (n = 94).

They can perhaps best be regarded as physical upper bounds to any effective limit on global population. The next largest value obtained was 1030 billion people, in a study that assessed the maximum potential photosynthetic productivity of land by modeling heterogeneous (climate and soil) characteristics for multiple regions.

As shown in figure 2, the estimated world population limit for most studies was above the actual population level at the time of the study, suggesting that the monotone time trend associated with world population growth gives rise to a gradually increasing time trend of the estimated population limit. On the other hand, the variance of estimates seems to increase over time as well. (The three extreme estimates mentioned above are left out of figure 2 to allow for reasonable scaling of the vertical axis.)

Although most studies—and all studies before 1940—generated a limit above the actual world population level, 22% of all studies (21 of 94 estimates, 17 of these coming from 6 studies) suggested that the world population level already surpassed the limit. Note especially the group of very strict limits for 1970. All these limits belong to a single study (Hulett 1970) and relate to different resources (aluminum, fertilizer, steel, wood, and food). The estimates for population limits from this study range from 0.5 billion to 1.2 billion, whereas the actual population level in 1970 was 3.7 billion. This study represents the pessimistic position in the growth debate, a debate that has raged since the 1960s and is reflected by an increase in the number of studies since then (figure 2b).

Table 2 presents summary statistics for the estimated population limits and their natural logarithms. The mean and

Box 1. Primary studies in the meta-analysis

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continued

median values for the absolute values differ extremely, because the mean is completely dominated by the maximum value. The median value, which is not sensitive to outliers, is 7.7 billion. As figure 1 illustrates, the most frequently mentioned limit is even lower, between 2 billion and 3 billion. The broad range for the absolute value, as reflected by the standard deviation, suggests that an analysis of the natural logarithm (ln) is more useful than an analysis of the mean or median absolute value.

Next, we consider conditional descriptive statistics. Table 3 shows these statistics for each of the seven methods applied in the studies we analyzed. The methods that appeared most frequently, excluding categorical assertion, were spatial extrapolation (42 observations), actual supply of a resource (20 observations), and modeling of multiple regions (15

observations). The lowest mean estimates of human population limits were based on the actual supply of a resource, on dynamic systems modeling, and on categorical assertion. This is not surprising: Basing estimates on the actual supply of a resource will generate conservative estimates by definition, dynamic systems modeling is the only approach that can combine multiple limiting factors, and categorical assertion may reflect the pessimism of its practitioners. The highest value was obtained with hypothetical modeling, which includes all three of the extreme values mentioned before.

Conditional statistics for different limiting factors are shown in table 4. The highest values for human population limits are found for carbon and heat removal, which were combined in primary studies with the hypothetical modeling method to examine how many people Earth can carry,

Box 1, continued

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Note: The primary coded data can be obtained from the authors of this article.

looking only at the availability of carbon in organic material and at the capacity to remove body heat. Given these approaches, the associated limits can be regarded as absolute physical limits that may serve as upper boundaries to effective limits. The table further shows that nonrenewable resources, forest products, and water availability cause the most restrictive population limits, followed by a synergy of multiple factors. Land (including food) and energy turn out to be almost equally restrictive.

Regression analysis

Here we present a meta-regression analysis that can be used to provide a better insight into which factors are important in assessing a limit to the world population. In addition, it will be used to present predictions involving multiple conditions on variables in the section “Meta-estimates of the global population limit,” below.

A basic ordinary least squares regression (not shown here) of the natural logarithm of estimated population limit, incorporating the full set of estimates (115 observations, including primary studies using categorical assertion), showed an insignificant coefficient of the variable “categorical assertion,” which indicates that there is no systematic bias in these studies compared with the rest of the sample. Since these studies lack a clear method, and thus are in essence extremely subjective, we performed a regression analysis excluding them (i.e., using 94 instead of 115 estimates). This regression (also not shown) did not yield significant estimates and thus did not deliver a very clear picture of the effects of excluding these studies. The reason was that the only two variables with significant coefficients, carbon and heat removal, were used in studies with extreme values for the dependent variable: 4.8×10^{14} and 1×10^{21} billion people for carbon and 1×10^9 billion people for heat removal. As argued in the section above on descriptive statistics, these extreme values are better regarded as upper bounds to limits than as actual limits, and leaving them out should improve the quality of the estimations. We performed a third regression analysis leaving out these values, which yielded the results shown in table 5.

The dependent variable is the natural logarithm of the estimated population limit. The independent meta-variables were defined in the section on database construction. Of the dummy variables based on method, “actual supply of a resource” was left out to serve as a reference dummy: Among all the methods, it was associated with the lowest average population limit estimate conditional on method. This makes interpretation of the coefficients of the method-based dummy variables relatively easy. For similar reasons, water availability was left out of the limiting-factor dummy variables.

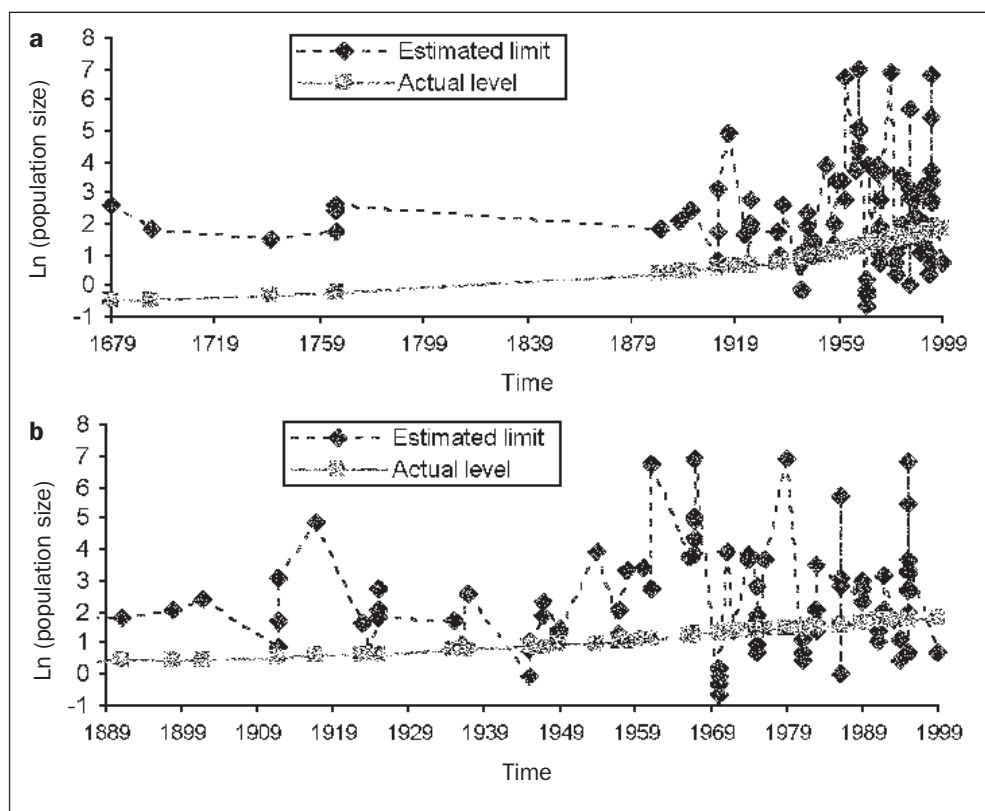


Figure 2. (a) Natural logarithm (ln) of actual population size and of estimated population limit (both in billions of people) from 1679 through 1999 (n = 91). (b) Enlargement showing the same measures from 1889 through 1999.

Estimated population limit	Mean	Standard deviation	Median	Minimum value	Maximum value
Based on absolute values (in billions)	1.05×10^{19}	1.03×10^{20}	7.7	0.5	1×10^{21}
Based on ln (billions)	3.34	6.18	2.04	-0.69	48.35

We performed the meta-regressions both with and without land- and food-related variables. The results that include these variables are linked to the methods “spatial extrapolation” and “modeling of multiple regions” and to the limiting variable “land/food.”

Note that dummy variables were defined to account for the missing data on land availability and energy intake. The insignificance, sign, and magnitude of the estimated coefficients indicate that no serious bias resulted from the missing data. In addition, because the two variables “dynamic systems modeling” and “synergy of multiple factors” are perfectly correlated (identical), as are “temporal extrapolation” and “limiting factor not identified,” we integrated the two limiting factors within each pair of variables in the regression equation. The resulting variables can be interpreted in two ways, namely, as method dummies or as limiting-factor dummies.

The results of the meta-regressions shown in table 5 can be interpreted as follows: All signs of estimated coefficients are in line with our expectations. The coefficients of the natural logarithm of actual population level are rather high (0.60 and 0.85), which suggests that the current population level is an important—even if implicit—benchmark when assessing a population limit. As long as population grows, this means that there is no absolute limit, but instead one that changes over time. Technology has an expected positive effect on population limits.

The coefficients associated with the methods and limiting factors are in line with the picture sketched by the univariate results in the section on descriptive statistics. The coefficient for hypothetical modeling is not significant, because extreme values were omitted from the regression. The variable “temporal extrapolation/limiting factor not identified” has a relatively high coefficient, because it combines the method and limiting-factor effects. Note that the averages of the coefficients

for methods and limiting factors (model 2) are 1.41 and 2.80, respectively. The sum of these averages is 4.21, and the range of the sum of the two types of coefficients is 2.27–6.43. The coefficient of “temporal extrapolation/limiting factor not identified” is thus slightly above the average and well within the range of all method–limiting factor combinations. Moreover, excluding land-related variables leads to a lower estimate for “temporal extrapolation/limiting factor not identified” (table 5, model 1). The smaller coefficient of “dynamic systems modeling/synergy of multiple factors,” which also combines these two effects, is in line with the univariate result found earlier, in that it generates on average a more conservative population limit. Nonrenewable resources, forest products, and dynamic systems modeling/synergy of multiple factors lead to the most restrictive estimate. The land- and food-related variables “land availability” and “energy intake” have expected signs: More land availability or less energy need per person leads to a higher estimate of the population limit. “Diet spatially homogeneous” reflects whether or not diets were assumed to be identical across regions in multiregional studies. If they were, then the impact of relatively high energy intake values for richer countries was omitted, thus pushing up the population limit estimate.

Finally, testing for robustness of the analysis by omitting additional extreme values, namely, those in the range of 800 to 1030 (see figure 1), did not change the qualitative characteristics of the results.

Meta-estimates of the global population limit

In this section, we use the findings of the previous two sections to come up with meta-estimates of the global population limit (assuming it exists). The descriptive, univariate statistics provide the starting point. Meta-analysis indicates which factors are important. Nonrenewable resources, forest products, water availability, and synergy of multiple factors

Table 3. Population limits (natural logarithm of billions of people), conditional on method.

Method	Number of observations	Mean (mean absolute)	Standard deviation	Median	Minimum	Maximum
Spatial extrapolation	42	2.53 (44.7) ^a	1.31	2.42	0.69	6.82
Modeling of multiple regions	15	2.99 (95.0) ^a	1.54	2.59	1.39	6.93
Actual supply of a resource	20	1.09 (18.8) ^a	1.45	0.89	−0.69	5.70
Hypothetical modeling	11	11.87 (0.09 × 10 ¹⁹) ^a	15.79	3.91	0.41	48.35
Dynamic systems modeling	2	1.69 (5.8) ^a	0.50	1.69	1.34	2.04
Temporal extrapolation	4	2.18 (19.6) ^a	1.60	2.06	0.69	3.91
Total (excluding categorical assertion)	94					
Categorical assertion		2.06 (14.2) ^a	1.08	2.05	−0.16	4.61

a. Mean of absolute population level (billions).

Table 4. Population limits (natural logarithm of billions of people), conditional on limiting factor.

Limiting factor	Number of observations	Mean (mean absolute)	Standard deviation	Median	Minimum	Maximum
Land/food	71	2.43 (61.8) ^a	1.52	2.04	-0.11	6.93
Water availability	1	0.69 (2.0) ^a	—	0.69	0.69	0.69
Energy	3	2.44 (102.0) ^a	2.94	1.61	0	5.70
Carbon	4	22.90 (2.5 × 10 ²⁰) ^a	21.87	20.24	2.77	48.35
Heat removal	1	20.72 (1 × 10 ⁹) ^a	—	20.72	20.72	20.72
Primary production	4	2.78 (18.0) ^a	0.58	2.96	1.95	3.26
Forest products	1	0.18 (1.2) ^a	—	0.18	0.18	0.18
Nonrenewable resources	3	-0.39 (0.7) ^a	0.29	-0.36	-0.69	-0.11
Synergy of multiple factors	2	1.69 (5.8) ^a	0.50	1.69	1.34	2.04
Limiting factor not identified	4	2.18 (19.6) ^a	1.60	2.06	0.69	3.91
Total	94					

a. Mean of absolute population level (billions).

turn out to lead to the most conservative estimates of a global population limit, with mean values of approximately 0.7 billion, 1.2 billion, 2.0 billion, and 5.8 billion people, respectively. Primary production (photosynthesis), land/food, and energy come next, with mean values of 18.0 billion, 61.8 billion, and 102.0 billion people. If “limit” is interpreted as meaning simply the most restrictive estimate, then the best guess would seem to be 0.7 billion people. Taking “methods” as a starting point, the estimates based on dynamic systems modeling and actual supply of a resource generate the lowest mean, namely 5.8 billion and 18.8 billion, respectively. Efficient use of data suggests that the median of all method-oriented (objective) studies is a good estimate (the mean is biased upward by the extreme estimates). This leads to a limit of 7.7 billion people.

Next, we turn to the results of the multivariate regression analysis. A prediction that combines the most restrictive limiting factor and method of estimation can be made by using a meta-regression model without land- and food-related variables (table 5, model 1). Two estimates can be calculated, namely, a lower and an upper bound, by setting all dummy variables at 0 or 1 for technology, methodological parameters, land availability, and energy intake. All statistically insignificant estimates are set equal to 0. The current population (for the year 2003) is set at 6.3 billion people. Given a lognormal distribution, the predicted absolute mean is the exponent (exp) of (mean + 0.5 × variance), where mean and variance relate to the distribution of predicted values with the estimated lognormal model (table 5) for all observations (independent variables). The variance of the estimate of model 1 in table

5 equals (1.02)². The most conservative estimate is then equal to

$$\exp[-2.05 + 0.60 \times \ln(6.3) + 0.5 \times (1.02)^2] = 0.65 \text{ billion people.}$$

This estimate is based on a low technological future (current technology), with water availability as the restrictive limiting factor. The most progressive estimate based on a consistent combination of method and limiting factor for current technology is equal to

$$\exp[-2.05 + 0.60 \times \ln(6.3) + 0.92 + 4.09 + 0.5 \times (1.02)^2] = 98 \text{ billion people.}$$

This estimate is based on carbon as a limiting factor. For best (future) technology, we obtain

$$\exp[-2.05 + 0.60 \times \ln(6.3) + 1.08 + 0.92 + 4.09 + 0.5 \times (1.02)^2] = 288 \text{ billion people.}$$

Obviously, the results depend strongly on the limiting factor considered.

When we take the most frequently studied limiting factor, land/food, the most conservative and progressive estimates, respectively, can be calculated as follows:

$$\exp[-2.05 + 0.60 \times \ln(6.3) + 1.67 + 2.26 + 0.5 \times (1.02)^2] = 33 \text{ billion people,}$$

and

$$\exp[-2.05 + 0.60 \times \ln(6.3) + 1.08 + 1.72 + 2.26 + 0.5 \times (1.02)^2] = 103 \text{ billion people.}$$

Of course, as not all countries are in possession of the best technology, the high estimates may be somewhat unrealistic or at best futuristic.

The predicted ranges are clearly much narrower than the range of estimates of primary studies (table 2). This is a

Table 5. Meta-regressions (ordinary least squares) of the natural logarithm of estimated population limit without (model 1) and with (model 2) land- and food-related variables, excluding the three highest estimates.

Variable	Model 1		Model 2	
	Coefficient	t-value	Coefficient	t-value
Constant	-2.05	-1.30	-3.36	-1.81
Natural logarithm of actual population level	0.60 ^a	2.10	0.85 ^a	3.28
Technology	1.08 ^a	2.27	0.64	1.38
Method				
Spatial extrapolation	1.67 ^a	3.55	1.36 ^a	2.58
Modeling of multiple regions	1.72 ^a	2.98	2.00 ^a	3.20
Hypothetical modeling	0.92	1.21	0.88	1.30
Limiting factor				
Land/food	2.26	1.60	2.41	1.84
Energy	3.54 ^a	2.13	3.61 ^a	2.39
Carbon	4.09 ^a	2.22	4.43 ^a	2.74
Primary production	3.10	1.93	3.03 ^a	2.14
Forest products	1.45	0.72	1.95	1.08
Nonrenewable resources	0.88	0.53	1.39	0.91
Method and limiting factor				
Dynamic systems modeling/synergy of multiple factors	2.83	1.61	2.39	1.54
Temporal extrapolation/limiting factor not identified	3.57 ^a	2.19	4.89 ^a	3.07
Land- and food-related variables				
Diet spatially homogeneous			1.46 ^a	2.52
Land availability			1.52 ^a	3.58
Energy intake			-1.08 ^a	-3.26
Dummy for missing "land availability"			0.09	0.21
Dummy for missing "energy intake"			-0.38	-0.86
Number of observations	91		91	
R ²	0.40		0.59	
Adjusted R ²	0.29		0.48	

Note: Heat removal was dropped as a limiting factor because, after excluding the three extremely high estimates, no observations were associated with it. Water availability is the reference dummy for limiting factors; actual supply of a resource is the reference dummy for methods.

a. Denotes significance at 5%.

logical aggregation outcome of statistical analysis. Note that current demography-based projections of a stabilized world population are far beyond the lower boundary (0.65 billion) and slightly above the median (7.7 billion) of all method-oriented studies. For example, Lutz and colleagues (2001) provide an estimate of 8.951 billion people, reached most probably around 2075. The United Nations predicts a world population of 8.9 billion people for 2050 (UN 2002). Note that these values do not refer to a limit for world population but are the outcome of demographic projections.

Most studies estimate a limit that is above the actual world population. If we assume, on the basis of this finding, that the actual limit is likely to be higher than the current (2003) world population of 6.3 billion, then the estimate of 0.7 billion mentioned earlier is unsuitable, while the median of all the studies, 7.7 billion, is just acceptable as an estimate. Of course, this approach can be criticized because although actual population levels may have been sustainable in the past, they are not necessarily so at this moment. Indeed, the latter view finds strong support from indicators of unsustainability such as global warming and biodiversity loss, which have not been taken into account in the primary studies analyzed here. These indicators suggest that the lower bound predic-

tion of 0.65 billion people in the meta-regression may be as good a guess as is possible for population limits in the current technological circumstances.

Concluding remarks

A meta-analysis of global population limit studies has two advantages. First, it allows us to assess the relative effect both of the studies' methods and of the limiting factors on which they focus. Second, it allows for a sophisticated meta-estimation of limits, which uses much more information than any single primary study.

A first striking result of the meta-analysis is that recent predictions of stabilized world population levels for 2050 exceed several of the meta-estimates of world population limits presented here. Therefore, even if the world population stabilizes in the future, this cannot be taken as a guarantee that the population level reached will be environmentally sustainable.

A second striking result is the substantial elasticity of the limit population with respect to the actual population at the time of the study. In each time period, the estimate of the limit population is strongly positively related to the present population size, with other relevant factors being the methodological features of the study and the limiting factors

considered. The actual population appears to function as an implicit frame of reference for the various studies. Projected limit levels of the world population reflect the situation at the time of the study, with a mark-up (or mark-down) factor to take into account technological change and specific limiting factors.

The meta-analysis sheds light on the most stringent limiting factors for the world population and hence on the scarce resources that matter most. These are not land, food, or energy—limiting factors that have received abundant attention in the various studies—but other factors that have received little attention thus far, such as fresh water availability, forest products, and nonrenewable products such as fertilizer. These understudied limiting factors are important candidates for research. Possible ways to moderate these limits, such as finding substitutes (for example, synthetic products may be substituted for wood), improving recycling technologies, and introducing advanced methods of fresh water production, conservation, and storage, need to be considered. These considerations inevitably lead to more refined and complex approaches than are found in most of the studies covered in this survey. Indeed, in many cases a limiting factor of one resource type can be moderated by the use of another resource, but then this second resource may ultimately become the most stringent limiting factor. Surprisingly, a large number of the studies focus on only one critical constraint. The dynamic systems modeling studies are an exception, but they tend to be aggregate and therefore abstract.

This analysis could be improved by adding indicators of the quality of studies or methods. However, this addition would introduce an element of subjectivity, and for this reason we have not pursued it here. Cohen (1995) offers a starting point for such an approach by critically examining a number of studies and their methods, but he is very cautious in his overall judgment, and he certainly does not arrive at anything close to an evaluation, ranking, or weighting. A framework based on data quality pedigrees, such as that proposed by Costanza and colleagues (1992), might reduce subjectivity in the process of capturing approaches with varying quality (implying meta-data of varying quality) using quantitative indicators. However, all methods can be criticized in one way or another. For instance, approaches using some type of spatial extrapolation tend to overestimate the potential population because they neglect trade effects (i.e., the support of densely populated, urban regions or countries by the rest of the world through imports of goods and resources and exports of waste). Virtually all primary studies can be regarded as partial and incomplete from some perspective that defies comparison with other methods.

Future analyses might weight the studies to reflect the idea that recent estimates are based on more reliable data and methods than early estimates. Because the estimates show a clear positive trend over time, this procedure would lead to somewhat higher meta-estimates of the global population limit

than the ones we derived. The more the recent studies dominated in the meta-analysis, the larger the deviation would be.

Fundamental inventions or macroinventions (also called revolutions), such as the Neolithic Revolution (the rise of agriculture), the Industrial Revolution (also affecting food processing technology), and the Green Revolution, have been able to raise food limits. A revolution in genetic technology, which has just been set in motion, may continue the long-run trend of food-related technological revolutions. In addition, despite widespread support for trade as an exchange that benefits all partners, human societies worldwide have not yet reaped all the potential benefits of global food trade. In this sense, globalization may perhaps be successful in terms of moderating food limits. Any remaining efficiency limits may be weakened through information and computer technologies, thus reducing human dependence on materials. On the other hand, rising incomes may lead to more material consumption per capita and richer diets, and thus to more stringent population limits. Ultimately, uncertainty about population limits remains large.

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