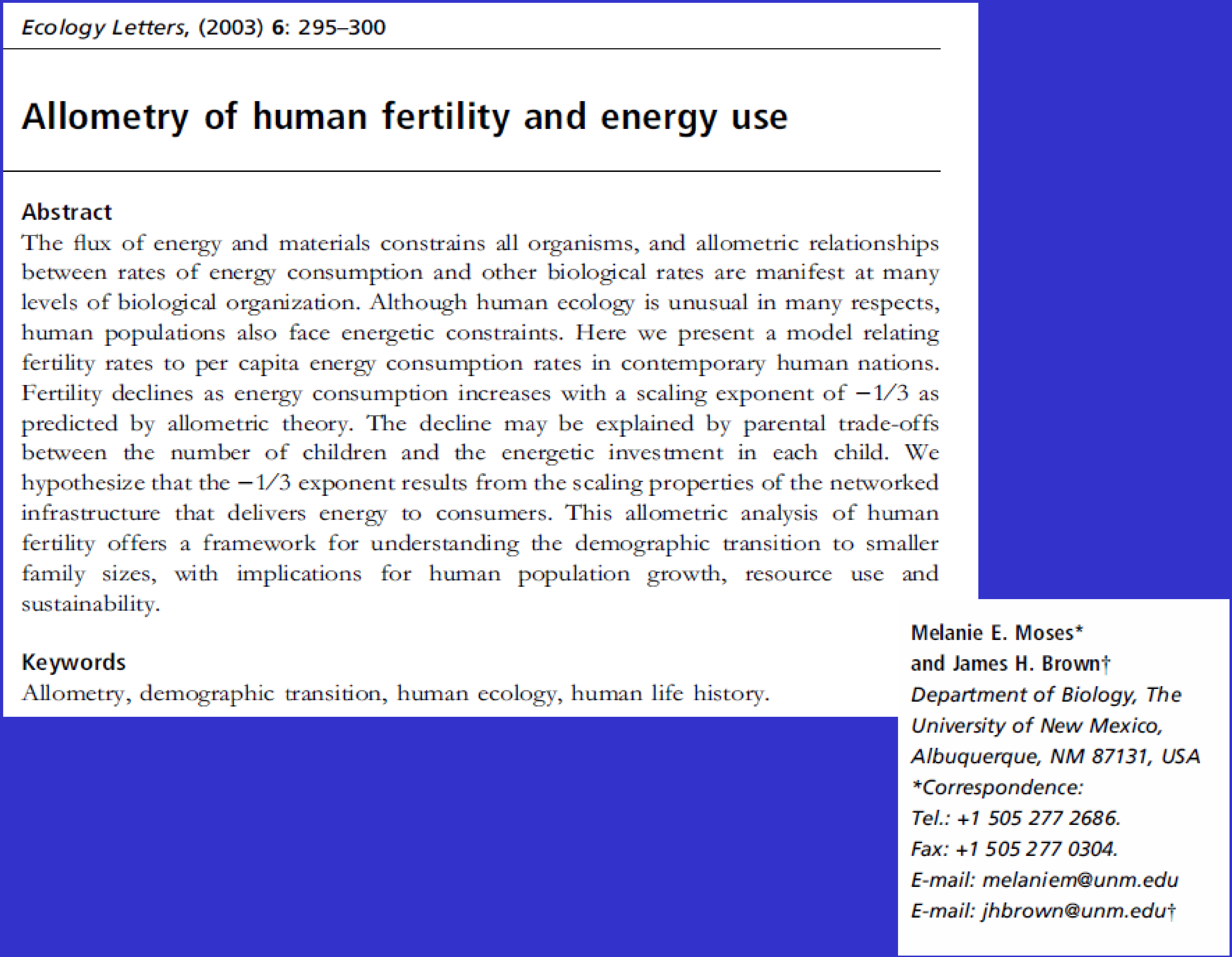


Ecology Letters, (2003) **6**: 295–300

Allometry of human fertility and energy use

Abstract

The flux of energy and materials constrains all organisms, and allometric relationships between rates of energy consumption and other biological rates are manifest at many levels of biological organization. Although human ecology is unusual in many respects, human populations also face energetic constraints. Here we present a model relating fertility rates to per capita energy consumption rates in contemporary human nations. Fertility declines as energy consumption increases with a scaling exponent of $-1/3$ as predicted by allometric theory. The decline may be explained by parental trade-offs between the number of children and the energetic investment in each child. We hypothesize that the $-1/3$ exponent results from the scaling properties of the networked infrastructure that delivers energy to consumers. This allometric analysis of human fertility offers a framework for understanding the demographic transition to smaller family sizes, with implications for human population growth, resource use and sustainability.

Keywords

Allometry, demographic transition, human ecology, human life history.

Melanie E. Moses*
and James H. Brown†
Department of Biology, The University of New Mexico, Albuquerque, NM 87131, USA
**Correspondence:*
Tel.: +1 505 277 2686.
Fax: +1 505 277 0304.
E-mail: melaniem@unm.edu
E-mail: jhbrown@unm.edu†

Allometry

Body size =S

(e.g., body mass)

Metabolism =M

(e.g., energy consumption)

Biological rates/times =R

(e.g., heart rare, reproductive rate)

Organisms have been selected to maximize metabolic capacity and the efficiency of internal energy transport

Allometric equations

$$M = a \times S^{0.75}$$

$\langle\text{energy consumption}\rangle = a \times \langle\text{body mass}\rangle^{0.75}$

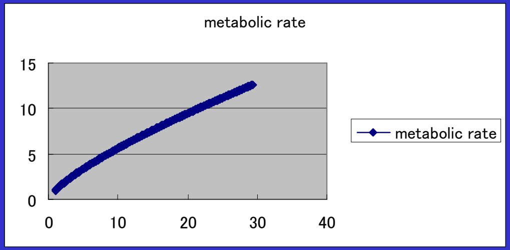
$$R = b \times S^{-0.25}$$

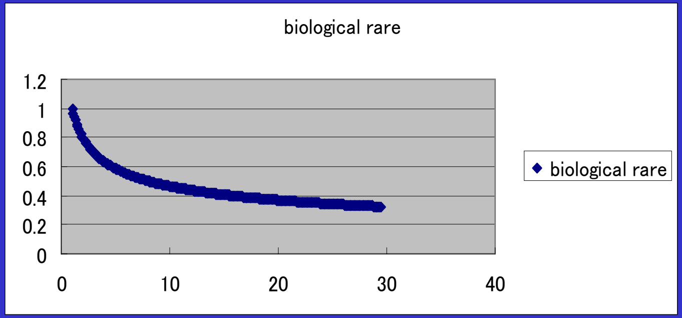
$\langle\text{reproductive rate}\rangle = b \times \langle\text{body mass}\rangle^{-0.25}$

$$R = c \times M^{-0.33}$$

$\langle\text{reproductive rate}\rangle = c \times \langle\text{energy consumption}\rangle^{-0.33}$

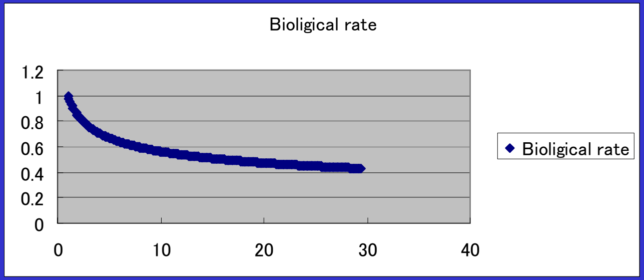
Energy consumption





Body size

Biological rate



Allometric relationships can be found at many levels of biological organization

- Mitochondrial activity within cells
- Growth rate of populations
- Fertility rate of mammals
  Fertility, body size, energy consumption

$$\text{Fertility} = b \times \text{body mass}^{-0.25}$$

$$\text{Fertility} = c \times \text{energy consumption}^{-0.33}$$

Applicable for humans?

- physiological energy consumption = a × body mass$^{0.75}$
- natural fertility = c × physiological energy consumption$^{-0.33}$
- natural fertility = b × body mass$^{-0.25}$

e.g., 120 watts/day = 5.66 × 60kg$^{0.75}$

Unique characteristics of humans

Fertility ≠ natural fertility

Energy consumption
=physiological metabolic rate
+ extra-metabolic energy
(e.g., gas, oil, coal, nuclear)

↙

11000W (USA) = 100 × physiological energy consumption
= 30,000 kg of primates

Objective: to test whether

allometric theory explains the relationships between increased per capita energy consumption and decrease in fertility at nation level?

Industrialization → fertility transition?

Data

1. For over 100 nations, 1970-1997
    - TFR, crude fertility, IMR
    - Per capita energy consumption

2. USA, 1850-2000
    - TFR, crude fertility
    - Per capita energy consumption

3. For mammals
    - body mass (Ernest et al, in press)
    - fertility (Earnest et al., in press)

Methods

$$\text{fertility} = c \times \text{energy consumption}^{-X}$$

$$\text{Log (fertility)} = -X \text{ Log (energy consumption)} + C$$

Ordinary least squares regression

$-X=0.33$?? Allometric theory ??

Results

1. For over 100 nations, 1970-1997
   - TFR, crude fertility, IMR
   - Per capita energy consumption

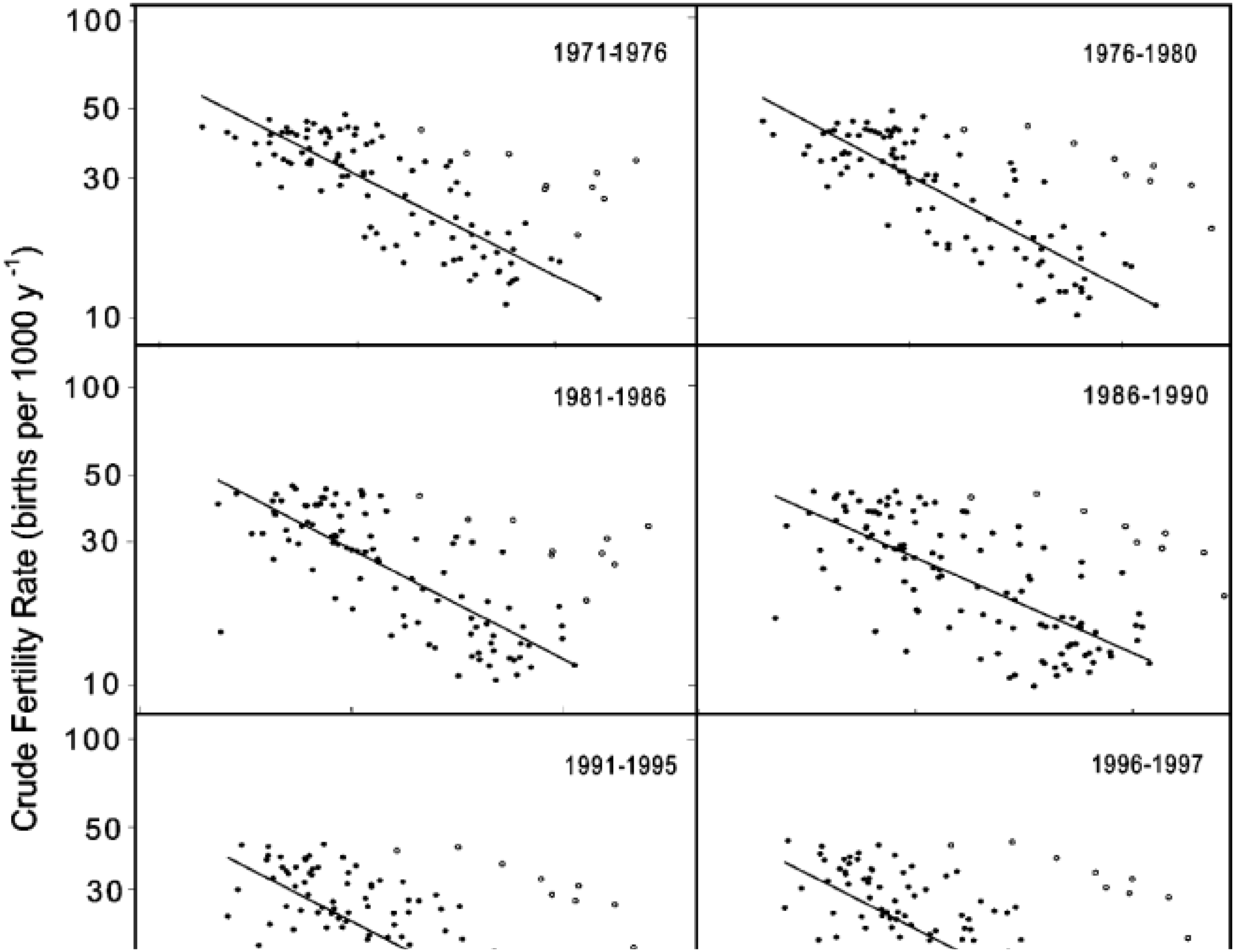


Figure 1 Annual human fertility rates (births per 1000 per year) plotted on logarithmic axes as a function of extra-metabolic energy consumption (E) for 98–116 nations in 6 periods from 1971 to 1997. Here infant mortality is subtracted from fertility to more accurately estimate the number of children actually raised by parents. Empty circles represent outliers (all of these nations were major oil producers) not included in the regression. The outliers in the lower left of the middle two panels are Latvia and Bosnia. The slopes of the 6 regressions are between −0.33 and −0.37. These values are statistically indistinguishable from the predicted value of −1/3 ($P > 0.10$ in all cases). The intercepts range from 2.43 to 2.59, with an average r^2 of 61%. Inclusion of outliers, excluding the effect of infant mortality, and considering total fertility rather than annual fertility have little effect on the slope of the relationship.

Results

1. For over 100 nations, 1970-1997
    - TFR, crude fertility, IMR
    - Per capita energy consumption

$$\text{Log (fertility)} = -X \text{ Log (energy consumption)} + C$$

$-X = -0.33 \sim -0.37 \fallingdotseq 0.33$

$C = 2.43 \sim 2.59$

Results

2. USA, 1850-2000
    - TFR, crude fertility
    - Per capita energy consumption

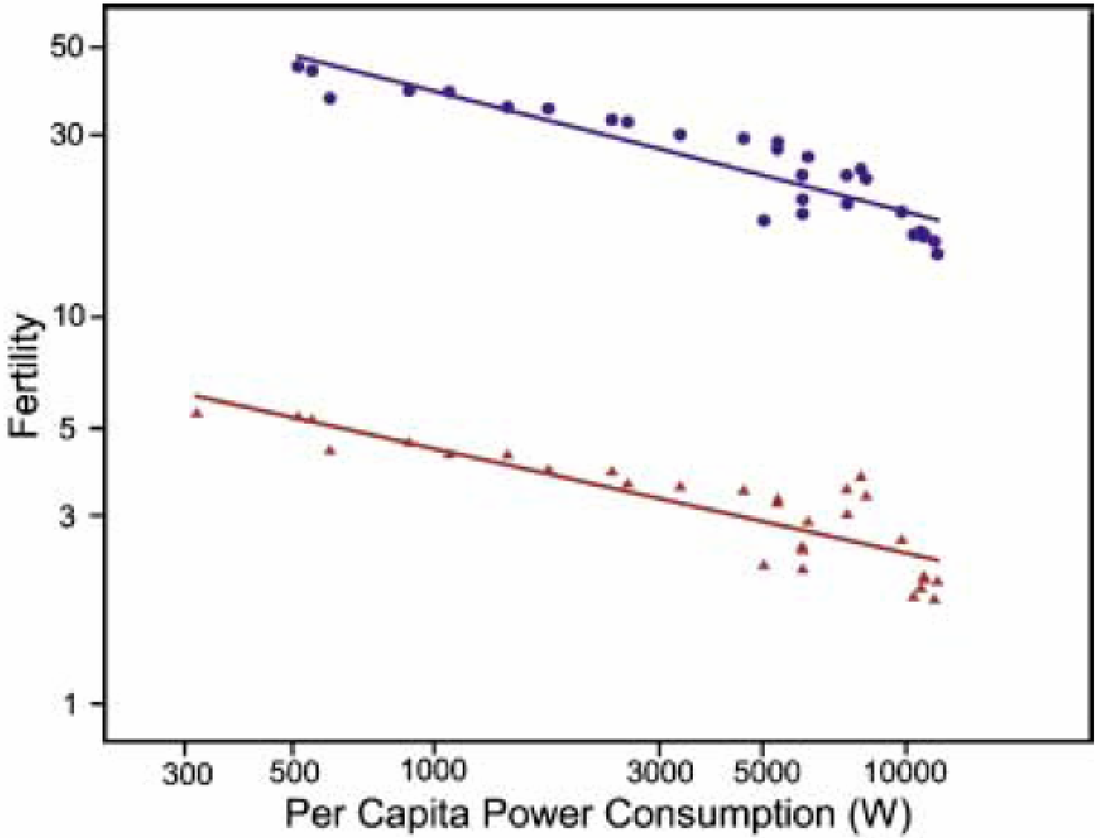


Figure 2 Human fertility in the USA as a function of extra-metabolic energy consumption (E) plotted on logarithmic axes. Data represent five-year intervals from 1850 through 2000. Circles represent crude fertility rate (births per thousand population) and triangles represent lifetime births per woman. The slope for crude fertility is −0.31 ($r^2 = 0.83$) and for total fertility is −0.27 ($r^2 = 0.76$).

Results

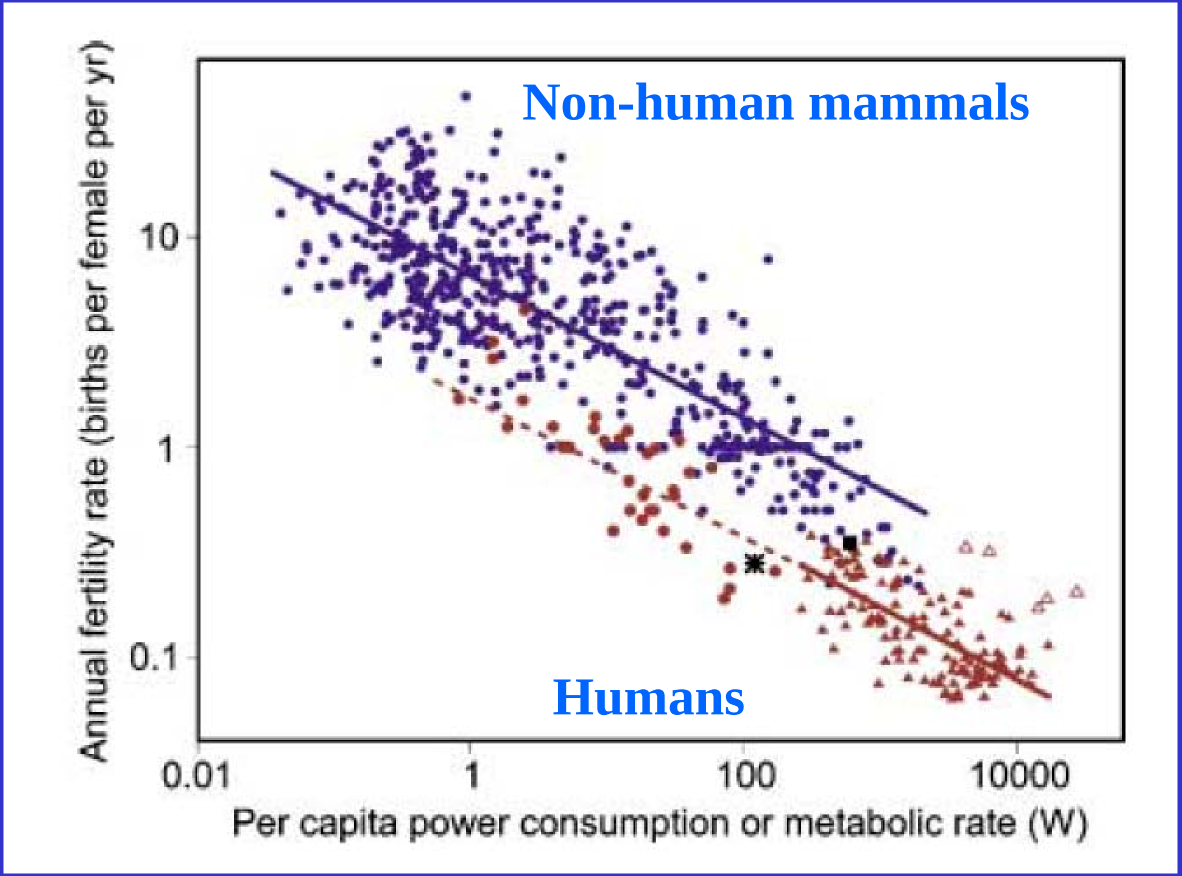
2. USA, 1850-2000
    - TFR, crude fertility
    - Per capita energy consumption

$$\text{Log (fertility)} = -X \text{ Log (energy consumption)} + C$$

$$-X = -0.31, -0.27 \doteqdot 0.33$$

Results

3. Relationships between fertility and energy consumption for mammals including human



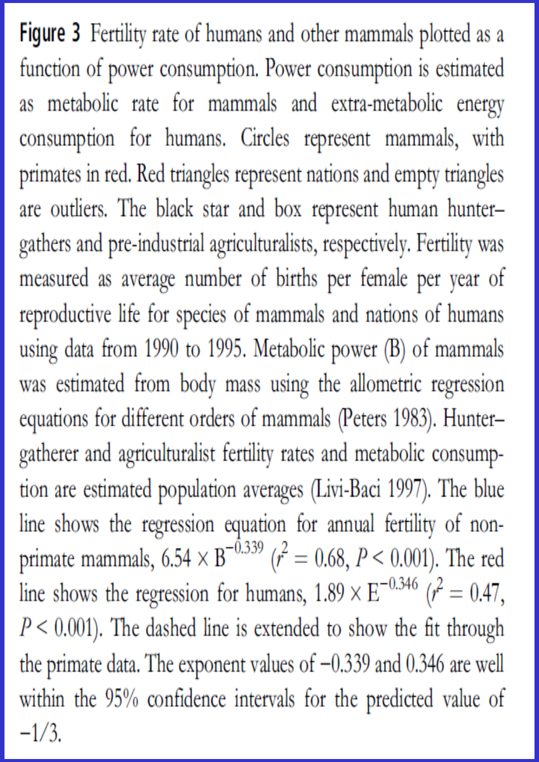


Figure 3 Fertility rate of humans and other mammals plotted as a function of power consumption. Power consumption is estimated as metabolic rate for mammals and extra-metabolic energy consumption for humans. Circles represent mammals, with primates in red. Red triangles represent nations and empty triangles are outliers. The black star and box represent human hunter–gathers and pre-industrial agriculturalists, respectively. Fertility was measured as average number of births per female per year of reproductive life for species of mammals and nations of humans using data from 1990 to 1995. Metabolic power (B) of mammals was estimated from body mass using the allometric regression equations for different orders of mammals (Peters 1983). Hunter–gatherer and agriculturalist fertility rates and metabolic consumption are estimated population averages (Livi-Baci 1997). The blue line shows the regression equation for annual fertility of non-primate mammals, $6.54 \times B^{-0.339}$ ($r^2 = 0.68$, $P < 0.001$). The red line shows the regression for humans, $1.89 \times E^{-0.346}$ ($r^2 = 0.47$, $P < 0.001$). The dashed line is extended to show the fit through the primate data. The exponent values of −0.339 and 0.346 are well within the 95% confidence intervals for the predicted value of −1/3.

Results

$$\mathrm{Log}\ (\mathrm{fertility}) = -X\ \mathrm{Log}\ (\mathrm{energy\ consumption}) + C$$

Non-promates mammals

$-X = -0.339 \fallingdotseq 0.33$
$C = 6.54$

Humans

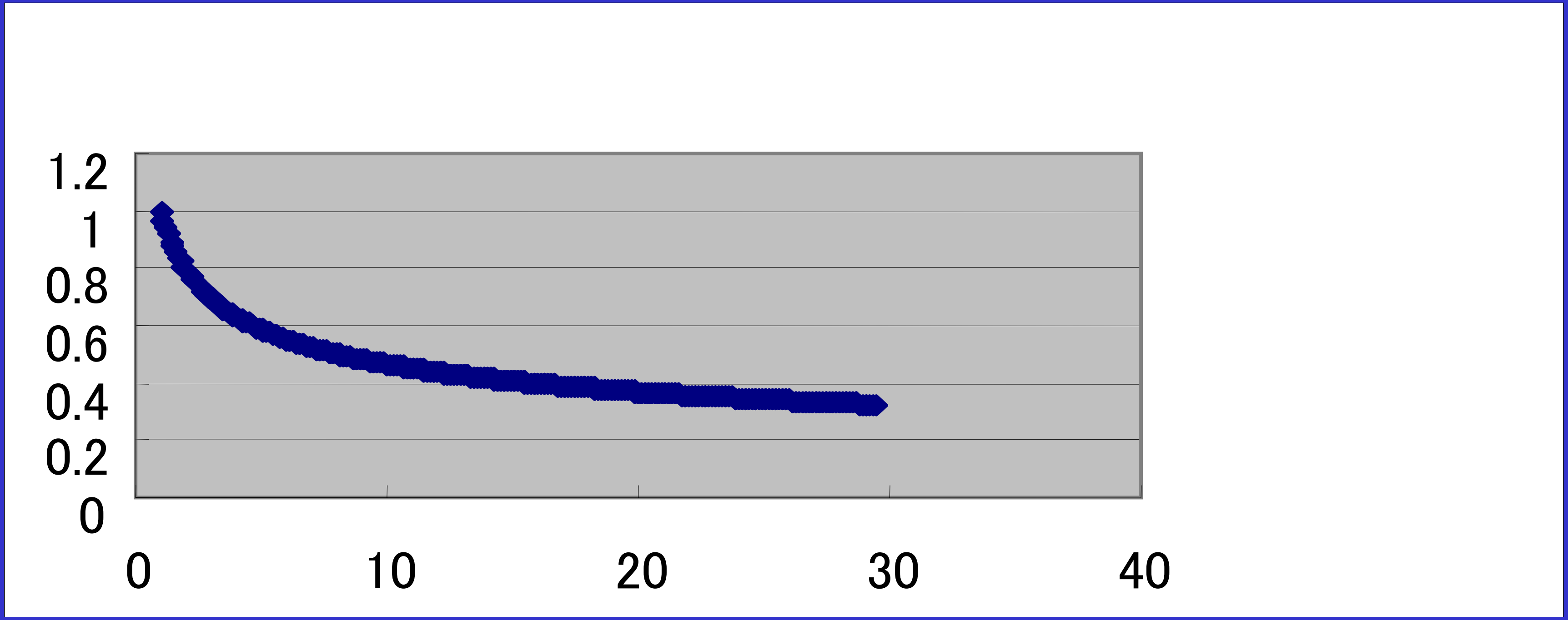
$-X = -0.346 \fallingdotseq 0.33$
$C = 1.89$

Findings:

1. Fertility rates of modern humans have decreased from the primates rate just as predicted by allometric theory (e.g., energy consumption)

2. Decline in human fertility is quantitatively consistent with the life-histry patterns of other mammals

Fertility



Energy consumption

Discussion

1. Why should human fertility decisions be guided by extra-metabolic energy consumption?

2. Why are these patterns quantitatively similar to those observed in primates and other mammals?

Trade-off between
① number of offspring and
② the energetic investment in each offspring

In the nations with higher energy consumption, more ② is required for the children to be competitive.

Allometric theory predicts:

65kg-mammals’ population density: $4/\text{km}^2$

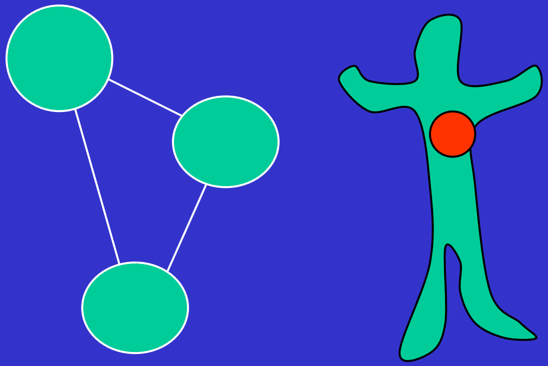
$1/\text{km}^2$ in pre-agricultural societies
$30/\text{km}^2$ in USA
$140/\text{km}^2$ in China

↑

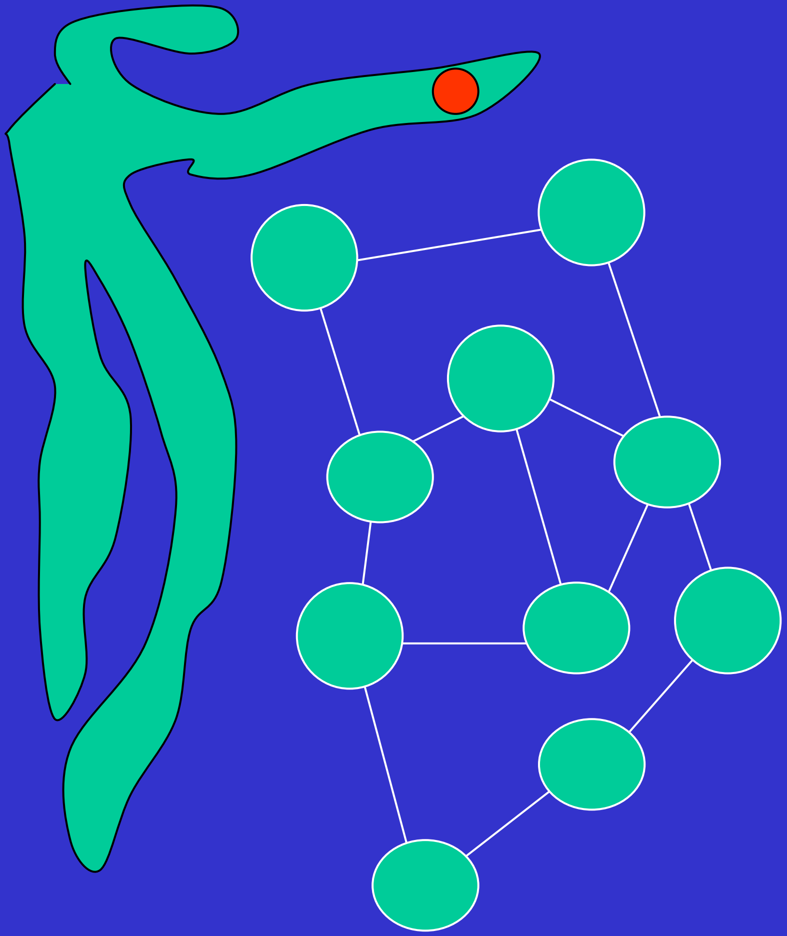
Extra-metabolic energy consumption

↓

Larger network of energy flow



Smaller network
Easy to obtain resource



Larger network
Longer time and distance to obtain resources
Larger energy required for each offspring

Utilization of natural resources by humans is not sustainable (Wackernagel et al., 2002)

Non-allometric energy consumption

Constrain to biological rate or fertility