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*Science* **337**, 1458 (2012);  
 DOI: 10.1126/science.1227620

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# A Measurable Planetary Boundary for the Biosphere

Steven W. Running

Forty years ago, Meadows *et al.* published a landmark first analysis of global limits to human activity (1). Based on a primitive computer model of the Earth system, they concluded that by the early decades of the 21st century, tangible limits to key global resources would begin to emerge. A reanalysis of the original results in 2008 found that the original global resource depletion projections were remarkably accurate (2). Since then, Rockström *et al.* (3) have defined a new term—planetary boundaries—to describe nine variables of high importance to habitability of Earth, including climate change, ocean acidification, land-use change, and biodiversity loss. These metrics are compelling conceptually, but many are not easily measured globally; explicitly defining a critical boundary is even more challenging. I suggest a new planetary boundary, terrestrial net primary (plant) production (NPP), that may be as compelling conceptually, integrates many of the currently defined variables, and is supported by an existing global data set for defining boundaries.

Terrestrial plant production is the foundation of the biospheric carbon cycle. Using solar energy, water and atmospheric CO<sub>2</sub> are transformed into plant carbohydrate matter. This plant matter then sustains the global food web and becomes the source of food, fiber, and fuel for humanity. NPP integrates aspects of five of the currently defined planetary boundaries: land-use change, freshwater use, biodiversity loss, and global nitrogen and phosphorus cycles. It is also influenced directly by two others, climate change and chemical pollution.

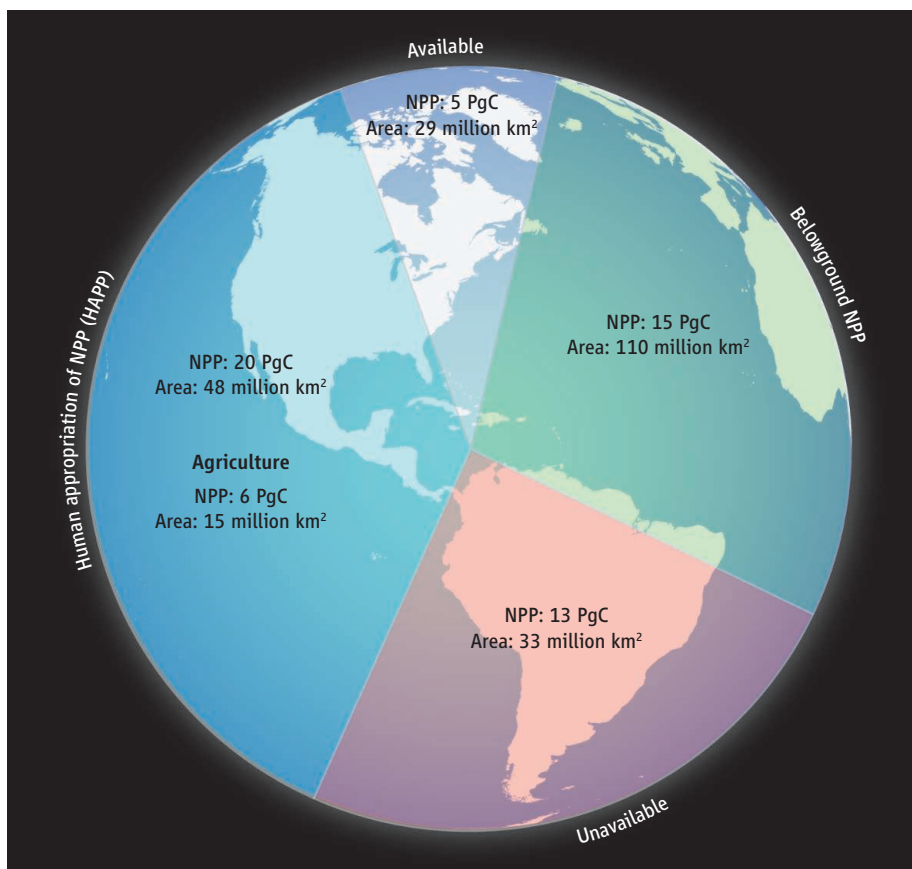
In 1986, Vitousek *et al.*, synthesizing many ground-based data sets, estimated that humans were consuming or directly co-opting 40% of biospheric production (4); they later postulated that humanity may one day consume all available NPP (5). Newer estimates that use satellite data but somewhat different assumptions agree that humans now co-opt roughly one-third of terrestrial NPP (6). Global NPP is now

derived from satellite measures of vegetated cover and density, combined with daily weather observations to analyze light, temperature, and water constraints to plant growth. In two recent papers, we presented the patterns and trends of global NPP, first from 1982 to 1999, where a small increase was observed (7), followed by an analysis with a new satellite from 2000 to 2010, where a small decrease was observed (8). However, looking at the complete data set, the most striking observation is that for more than 30 years, global NPP has stayed near 53.6 Pg per year, with only ~1 Pg of interannual variability. Thus, this key factor

Terrestrial net primary (plant) production provides a measurable boundary for human consumption of Earth's biological resources.

in the global carbon cycle seems to vary less than 2% annually.

This remarkable consistency of global NPP may be due to equally small global variability of the key drivers. The key global input of energy that drives photosynthesis, solar radiation, varies by less than 0.001% from year to year. Total global precipitation is thought to vary by only around 0.05 mm/day, or 2% each year. Thus, although there is huge regional variability within the Earth system—for example, due to droughts, floods, and heat and cold waves—the final planetary totals of energy and mass flows may average out.



**Will human consumption of primary plant production soon reach its limits?** In their original planetary boundaries diagram, Rockström *et al.* (3) identified three systems—climate change, rate of biodiversity loss, and human interference with the nitrogen cycle—that may already have exceeded their planetary boundary. However, many of these metrics are not easy to measure globally. Net primary production (NPP) integrates five of these boundaries and may be more easily measurable on a global scale. Consideration of current land use patterns and the projected rise in the human population suggest that human consumption may reach the global NPP boundary within the next few decades.

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If global NPP is fixed by planetary constraints, then no substantial increase in plant growth may be possible. Hence, the obvious policy question must be whether the biosphere can support the 40% increase in global population projected for 2050 and beyond.

To determine if humanity can co-opt a higher fraction of global NPP, the previously defined planetary boundaries become relevant, starting with land use. According to the most recent estimates from global satellite data sets, humans currently appropriate 38% of global NPP, which would appear to leave 62%, or about 33 Pg, available for future consumption (see the figure) (9). However, the authors also estimate that 53% of global NPP is not harvestable. This nonharvestable part includes plant growth in root systems, preserved land (for example, in national parks that are critical for ecosystem services and biodiversity), and wilderness areas where no transportation exists for harvesting. If one subtracts this unavailable NPP, only about 5 Pg, or 10% of total global NPP, theoretically remains for additional future use by humans.

Agriculture now consumes 38% of the global land surface, with major new expansion only available in underdeveloped parts of South America and Africa (10). Land put in to agriculture often has lower production than the natural ecosystem replaced, but growth is concentrated in the components that humans value. Crop production exceeds the natural

ecosystem when augmented with irrigation and fertilizer applications. Cropland under irrigation has roughly doubled in the last 50 years, and fertilizer use has increased by 500% (10).

Many analyses now conclude that freshwater use for irrigation has already reached a planetary boundary. As some rivers are completely drained for agriculture and groundwater withdrawal limits are reached in some regions, irrigated crop area could decrease in coming decades (11). Likewise, Rockström *et al.* (3) concluded that the nitrogen and phosphorus cycles may have already exceeded planetary boundaries, as evidenced by massive river pollution and ocean anaerobic dead zones. If anything, future increases in NPP must be achieved with less, not more, irrigation and fertilizer use.

Possibly the biggest unknown in this global analysis is the future of bioenergy. If every chloroplast of the remaining 5 Pg of NPP were used for bioenergy, only 40% of current global primary energy consumption would be satisfied (9). There will be very real policy dilemmas if land previously allocated to food production is transformed to bioenergy production, raising food prices for the people who can least afford it (12).

Any analysis of global biospheric limits includes many assumptions and considerable uncertainties. Yet, global monitoring will document every parcel of land that is

converted from a natural ecosystem to cities, agriculture, or bioenergy. Every such conversion increases the fraction of NPP consumed by humanity. The question is thus not whether humans will reach the global NPP boundary but when we will do so. The projected 40% increase in human population by 2050 CE, combined with goals to substantially improve standards of living for the poorest 5 billion people on Earth, implies at least a doubling of future resource demand by 2050. As suggested 40 years ago (1), the limits to growth as measured by human consumption of NPP may well be reached in the next few decades.

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**Acknowledgments:** I thank C. Cleveland, M. Zhao, and W. K. Smith for valuable discussions. NASA has provided financial support for the global net primary production data set since 1990.

10.1126/science.1227620

## MATERIALS SCIENCE

# Nanometer-Scale Printing

John A. Rogers

Progress in nanotechnology relies on the ability to fabricate structures with precisely defined, nanoscale dimensions. Historically, this task has been accomplished with energetic beams of electrons, ions, or photons, using sophisticated tools whose origins lie in the semiconductor industry (1). Although well suited for manufacturing of integrated circuits and related devices, such techniques are often not the best choices for exploratory research because they require expensive equipment and specialized facilities. They also tend to work well only with narrow classes of materials, and they can be prohibitively slow for use over large areas.

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On page 1517 of this issue, Liao *et al.* (2) introduce a scheme that bypasses these limitations, in which rubber stamps affect nanoscale pattern transfer via molecular-scale fracture. Their technique represents a conceptual advance on a class of “soft lithographic” methods in which elastomers with fine features of relief on their surfaces deliver molecules (3, 4) or materials (5, 6) onto substrates of interest, in a process of contact printing. By providing advanced nanofabrication capabilities to researchers with limited access to complex apparatus, these simple methods have played a central role in the emergence of nanotechnology as a broad, vibrant field of study.

The work of Liao *et al.* is important in this context because it enhances the resolution of one of the most widely used soft litho-

A method using rubber stamps and molecular-scale fracture can produce patterns with feature sizes in the nanometer range.

graphic techniques, in which stamps made of poly(dimethylsiloxane) (PDMS) print molecules onto substrate surfaces with which they covalently react to form densely packed, monolayer films, referred to as self-assembled monolayers (SAMs) (3). This process, even when carried out by hand in an ordinary laboratory environment, can yield patterns of SAMs with features as small as a fraction of a micrometer. Two aspects, however, frustrate operation in regimes of resolution that are relevant to the frontiers of modern nanotechnology (7–9). First, the molecules that form the SAMs diffuse slightly along the surface during and after printing, thereby blurring the edges of the patterns. Second, gas-phase transport can carry molecules from the recessed, noncontacting regions of the stamp to the substrate, yielding partial monolayers