The UN medium population projection is an unstable equilibrium

Peer-reviewed letter

Recent projections suggest that the global human population will reach a stable size of ~10 billion by the end of the 21st century (Lutz *et al.* 2001; UN 2011). These projections assume that people in all countries will pass through the "demographic transition", a pattern by which mortality and fertility decline with economic development, leading to high population growth during the transition but zero growth afterwards (Lee 2011).

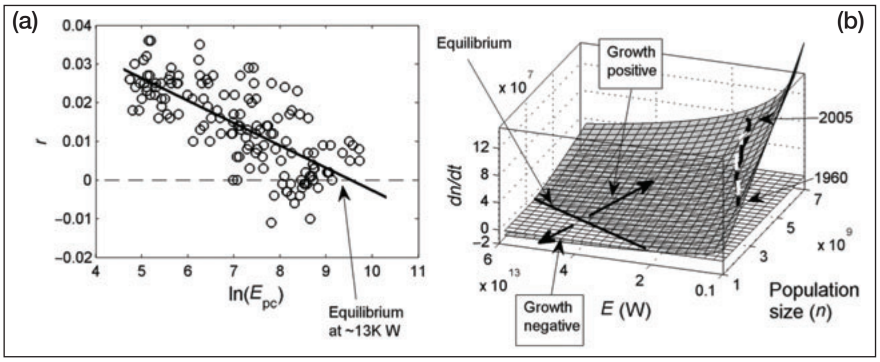

Figure 1. *Energy use and human population stability. (a) The dependence of country-level population growth on industrial energy use predicts a steady-state* (r = 0) *at ~13 000 W (after DeLong* et al. *[2010]). (b) For any global energy supply* (E)*, the slope of the relationship between* dn/dt *and* n *in our model is positive at the equilibrium (straight black line where the gray surface intersects zero). For the last half-century, the global population has been moving away from the equilibrium rather than toward it (white line is observed, black line is modeled), indicating that the UN projection of a stable population is increasingly less likely to occur.*

The prediction of sigmoidal ("S"-shaped) population growth gives the impression that the global population is approaching its carrying capacity, which is to say a stable equilibrium. But the United Nations (UN) projections consider neither the underlying dynamics of population growth nor demographic covariates such as resource constraints (Cohen 2003; Lee 2011), which prevents a stability analysis of the projections. Despite this, a population of ~10 billion is generally taken as an expectation around which social, economic, and environmental planning can be developed. We analyzed a model of the global human population and found that (1) the projected leveling-off is an unstable equilibrium and (2) the global population has been diverging from this equilibrium for decades, challenging the UN's medium forecast.

In a dynamic population model, equilibria occur wherever the absolute change in population size over time (dn/dt) equals zero. If an equilibrium is unstable, perturbations away from the equilibrium are amplified, but if it is stable the population returns to its equilibrium. For any model that predicts an equilibrium, its stability can be determined by the slope of dn/dt with respect to population size n at the equilibrium: it is stable if the slope is negative and unstable if positive. Our previous work indicated that the UN projection can be achieved if sufficient energy inputs to the global economy are made (DeLong *et al.* 2010). Our model – which makes population growth rate a function of per-capita energy use as

$$\frac{dn}{dt} = \left(a\ln\left[\frac{E}{n}\right] + b\right)n,$$

where a and b are fitted parameters and E is the global energy supply – suggests that the population will stop growing once each person has access to ~13 000 watts (W) per capita (Figure 1a). At the equilibrium population size

$$\hat{n} = E/\exp(-b/a),$$

the slope of dn/dt is $-a$; because a is always negative (growth rate declines with per-capita energy use and development; Figure 1a), the slope is positive and the equilibrium is unstable for all levels of E. We also numerically analyzed the stability of the model under various potential energy and population scenarios, because the size of future energy supplies and the link between energy availability and population size are both unknown. Under a wide range of combinations of E and n, dn/dt increases with population size at the equilibrium, making it unstable (Figure 1b). The equation for $\hat{n}$, with E in the numerator, also shows that global energy supplies do help to determine what the (unstable) equilibrium population size will be.

The unstable nature of the equilibrium indicates that we cannot expect the global population to stabilize at ~10 billion on its own; energy is required to "push" it toward this equilibrium state. Declines in energy availability or increases in population size will tend to push the population away from the equilibrium, and changes in both of these directions are already happening. Indeed, the observed population size and global energy availability trajectory for 1960 through 2005 is moving away from, not toward, the equilibrium, as per-capita energy supplies have not kept pace with population growth (Figure 1b, dashed white line; Nel and van Zyl 2010). This trajectory is well-predicted by our model given known energy supplies and population sizes (Figure 1b, black line).

The unstable equilibrium at ~13 000 W is a high-energy equilibrium (DeLong *et al.* 2010). It only occurs when humans have access to high levels of industrial energy that support high levels of economic development (Brown *et al.* 2011). This dependence of growth rate on energy in humans is opposite that of other populations in nature, for which stable equilibria occur when energy levels are low enough to make death rates equal birth rates (DeLong and Hanson 2009). Before the agricultural and technological revolutions that enabled humans to grow rapidly and dominate the biosphere, however, humans likely existed in a low-energy, or "Malthusian", steady-state, with population size regulated by energy or other resources (Galor and Moav 2001).

Global human population dynamics are tightly linked to the demographic transition (Lee 2011), which remains an unsolved life-history problem (Burger *et al.* 2011). Some researchers argue that a quantity–quality trade-off drives declining fertility to offset increasing per-child costs (Becker and Lewis 1973), but whatever the explanation, recognizing that the vital rates of modern humans are responsive to environmental inputs and not just functions of time is crucial for predicting future population growth. Also, the relationship between energy use and demographic rates may not be fixed (Myrskyla *et al.* 2009), so understanding how cultural, economic, political, and historical forces could alter the relationship is important because it determines the location of the equilibrium. Rapid changes in the availability of energy, such as the loss of key flows of fossil fuels or the development of alternative energy sources, could potentially alter population growth rates, but the time scale of the response to such changes will be unknown as long as the demographic transition remains unexplained.

There is growing concern that either too many or too few people could jeopardize the stability and prosperity of humanity, but it is unknown when and at what size the human population will stop growing. Yet sustainability requires a stable population, because energy and other resource demands increase with population size. Understanding human population dynamics is thus crucial for planning a sustainable future. With their wealth of experience in population ecology, ecologists can and should play a larger role in expanding our understanding of human population dynamics, but to date have mostly ignored such dynamics in their research. Current research emphasizes uncertainty in extrapolations rather than underlying mechanisms, and this must change. If ecologists began to include mechanistic models of the global population into studies on ecosystem services, climate change, and environmental management, we might develop a better sense of what lies ahead.

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Forest fire management, climate change, and the risk of catastrophic carbon losses

Peer-reviewed letter

Approaches to management of fire-prone forests are undergoing rapid change, driven by recognition that technological attempts to subdue fire at large scales (fire suppression) are ecologically and economically unsustainable. However, our current framework for intervention excludes the full scope of the fire management problem within the broader context of fire–vegetation–climate interactions. Climate change may already be causing unprecedented fire activity, and even if current fires are within the historical range of variability, models predict that current fire management problems will be compounded by more frequent extreme fire-conducive weather conditions (eg Fried *et al.* 2004). Concern about climate change has also made the mitigation of greenhouse-gas (GHG) emissions and increased carbon (C) storage a priority for forest managers.

A widely accepted fire management strategy is prescribed burning – purposefully setting fires under mild weather conditions to reduce fuel loads and the risk of subsequent high-severity wildfires. However, the potential for prescribed burning in some biomes to mitigate GHG emissions is contested. In northern Australia's eucalypt savannas, non-carbon-dioxide GHG emissions (eg methane, nitrous oxides) are being reduced as part of a voluntary C offset program, by setting fires early in the dry season when mild conditions prevail, thereby reducing fuel consumption and fire severity (Russell-Smith *et al.* 2009). By contrast, in southern Australia's less fire-prone eucalypt forests, this approach reportedly has little potential to reduce emissions (Bradstock *et al.* 2012), because the emissions from prescribed burning are likely to exceed the emissions avoided by reducing wildfire extent

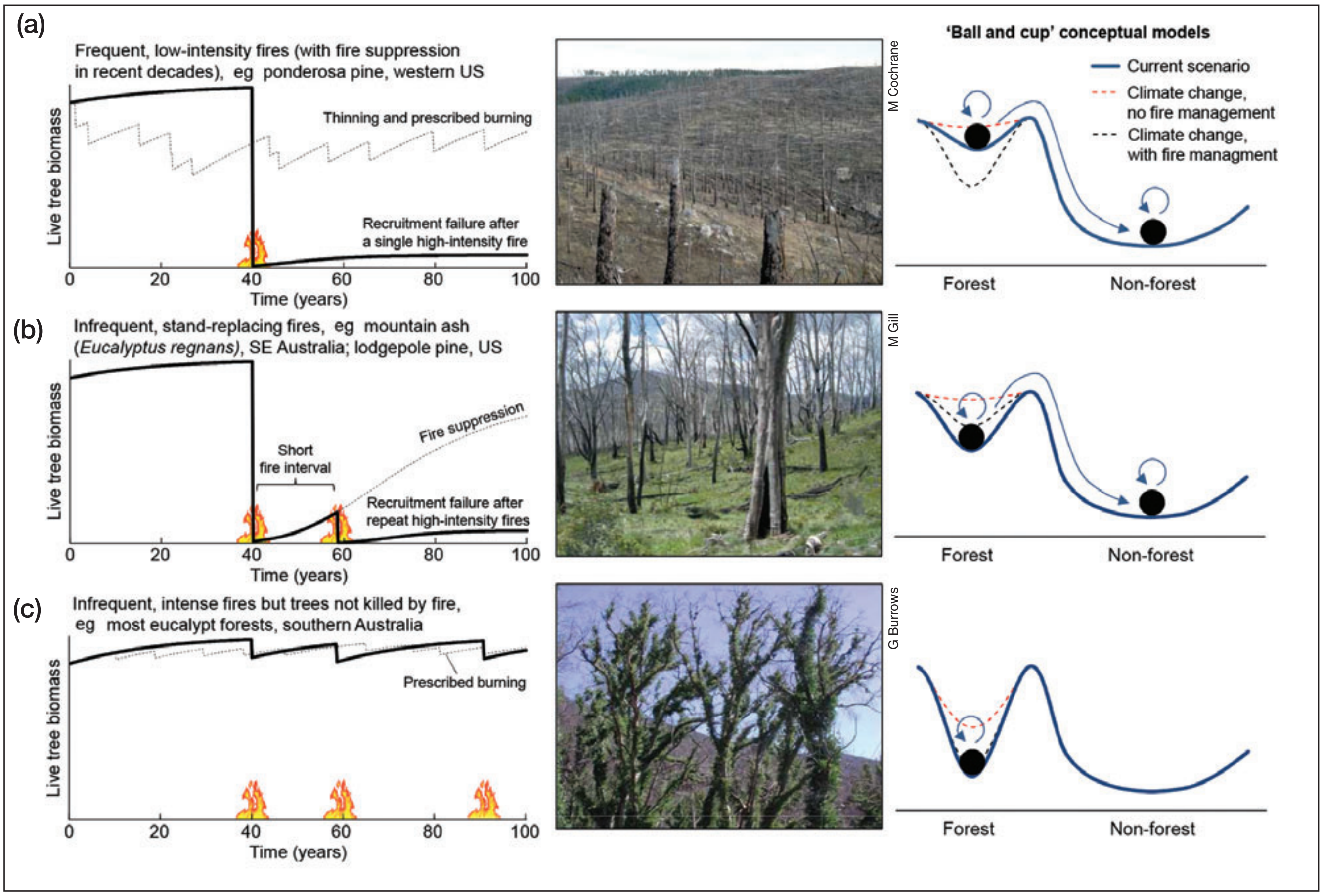

Figure 1. *Contrasting responses of forest biomass to wildfire and possible alternative fire management scenarios. (a) Representation of a forest adapted to frequent, low-severity fire, with historical fire suppression increasing the density of small trees and risk of stand-replacing fire. Such forests generally have limited regenerative capacity after stand-replacing fires, because seeds do not survive the fires and recruitment must come from offsite. Thinning and prescribed burning can decrease the risk of stand-replacement, potentially preventing long-term shifts to low-biomass states after regeneration failure (eg ponderosa pine [*Pinus ponderosa*], see image). (b) Representation of a forest adapted to infrequent, stand-replacing fire. Although seeds survive high-intensity fires (eg stored in canopy-borne serotinous cones), climate-driven reductions in intervals between stand-replacing fires can kill off immature regrowth, leading to subsequent regeneration failure. Under climate-change scenarios, the most appropriate management option for minimizing the risk of regeneration failure may be total fire suppression (eg alpine ash [*Eucalyptus delegatensis*], southeastern Australia, see image). (c) Representation of a forest experiencing infrequent, high-severity fires; the trees are highly resistant to fire because of their ability to resprout. Such forests are relatively resilient to changes in intervals between high-intensity fires because regeneration from seeds is unnecessary. Management to prevent fire-driven state shifts is not required (eg most eucalypt forests [*Eucalyptus* spp], southern Australia, see image).*

and intensity in treated landscapes. Indeed, in these systems, 3–4 areal units of prescribed fire are needed to avoid a single areal unit of wildfire (Boer *et al*. 2009; Price and Bradstock 2011). In the western US, prescribed burning for reducing GHG emissions from ponderosa pine forests is controversial. Fire suppression over the past century has caused a shift from surface- to crown-fire regimes, leading to an increase in tree density and fuel loads in these forests. Hurteau and Brooks (2011) posited that mechanical thinning, followed by the restoration of frequent, low-severity fires through prescribed burning, can increase the stability of live tree biomass by reducing the risk of stand-replacing wildfires. Although there is widespread acceptance that prescribed burning can reduce wildfire risk in these forests, Campbell *et al.* (2012) argued that the emissions from prescribed burning exceed the emissions avoided by reducing wildfire extent and intensity, thus rendering this approach ineffective in reducing GHG emissions. Clearly, a better understanding of the complex C trade-offs between prescribed fire and wildfire will be required before this important debate can be resolved.

A paradoxical feature of the debate about prescribed burning as a GHG mitigation tool is the limited consideration given to irreversible climate- and fire-driven conversion of high-biomass forests to low-biomass, non-forest states (Figure 1). Such "biome switching" is predicted by alternative stable state theory and accords with the fire ecology of some forest systems. Lindenmayer *et al.* (2011), for example, proposed the "landscape trap" concept, whereby strong feedbacks after logging of high-biomass eucalypt forests grossly inflate fire risk, making recovery to the pre-fire state unlikely. Alternative stable state theory can be similarly applied to climate-change impacts on many fire-prone forests. For instance, some fire-suppressed forests of the western US are vulnerable to conversion to non-forest states because of increasingly severe fire weather and prolonged drying. Indeed, modeling by Westerling *et al.* (2011) suggests that climate-driven increases in fire frequency over the next century could transform much of Wyoming's Greater Yellowstone Ecosystem from conifer forests to more open vegetation types.

For vulnerable forests, the real value of mechanical thinning and subsequent prescribed burning, as proposed by Hurteau and Brooks (2011), may be to resist biome switching, assuming that the "expenditure" of C associated with these interventions is substantially less than the avoided C losses associated with a biome switch (Figure 1a). In southern Australia's tallest eucalypt forests (Figure 1b), which are vulnerable to stand-replacing fires, broad-scale prescribed burning is impractical given the dominance of obligate-seeders. In this case, extensive thinning may increase fire risk, and fire suppression may be the best management option. In contrast, in fire-resistant eucalypt forest types, dominated by resprouting tree species, there is a low likelihood that climate change could alter fire regimes sufficiently to cause biome switching (Figure 1c). At the wildland–urban interface, the most cost-effective fire management strategy for reducing the threat to human life and property may be to focus on heavy localized thinning of forests through mechanical harvesting, prescribed burning, or grazing, regardless of forest regeneration strategies (eg Figure 1; Cochrane *et al.* 2012; Gibbons *et al.* 2012).

Crucial steps in better understanding the relative risks of both orthodox and unconventional fire management interventions require predicting the vulnerability of ecosystems to state transitions due to fire–climate interactions. Where the risk is high, discriminating various alternative management approaches demands assessment of the magnitude of C losses and the costs and benefits in terms of other ecosystem services, biodiversity values, and public safety. No single objective should define fire management, and an evidence-based understanding of the inherent tradeoffs between different fire management regimes is imperative.

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