Terrestrial ecosystem loss and biosphere collapse

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Abstract

Purpose – The purpose of this paper is to propose a measurable terrestrial ecosystem boundary to answer the question: what extent of landscapes, bioregions, continents, and the global Earth System must remain as connected and intact core ecological areas and agro-ecological buffers to sustain local and regional ecosystem services as well as the biosphere commons?

Design/methodology/approach – This observational study reviews planetary boundary, biosphere, climate, ecosystems, and ecological tipping point science. It presents a refinement to planetary boundary science to include a measurable terrestrial ecosystem boundary based on landscape ecology and percolation theory. The paper concludes with discussion of the urgency posed by ecosystem collapse.

Findings – A new planetary boundary threshold is proposed based on ecology's percolation theory: that across scales 60 percent of terrestrial ecosystems must remain, setting the boundary at 66 percent as a precaution, to maintain key biogeochemical processes that sustain the biosphere and for ecosystems to remain the context for human endeavors. Strict protection is proposed for 44 percent of global land, 22 percent as agro-ecological buffers, and 33 percent as zones of sustainable human use.

Research limitations/implications – It is not possible to carry out controlled experiments on Earth's one biosphere, removing landscape connectivity to see long-term effects results upon ecological well-being.

Practical implications – Spatially explicit goals for the amount and connectivity of natural and agro-ecological ecosystems to maintain ecological connectivity across scales may help in planning land use, including protection and placement of ecological restoration activities.

Originality/value – This paper proposes the first measureable and spatially explicit terrestrial ecosystem loss threshold as part of planetary boundary science.

Keywords Biosphere, Global ecological sustainability, Landscape connectivity, Percolation theory, Planetary boundary, Terrestrial ecosystems

Paper type General review

Introduction to planetary boundaries

From Malthus (1798), through Aldo Leopold's (1949) land ethic, to *The Limits to Growth* (Meadows *et al.*, 1972), the Millennium Ecosystem Assessment (2005), and finally current planetary boundary and global change science (Rockström *et al.*, 2009a, b) runs a strand of concern about human growth's impacts upon Earth's biophysical systems – terrestrial ecosystems in particular – and about requirements for global ecological sustainability, while avoiding biosphere collapse. Our biosphere is composed of Earth's thin mantle of life present at, and just above and below, the Earth's surface. Some have indicated that human impacts upon the biosphere are analogous to a large, uncontrolled experiment, which threatens its collapse (Trevors *et al.*, 2010). Little is known regarding what collapse of the biosphere would look like, how long it would take, what are its ecosystem and spatial patterns, and whether it is reversible or survivable. But it is

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becoming more widely recognized that Earth's ecosystem services depend fundamentally upon holistic, well-functioning natural systems (Cornell, 2012).

Accelerating human pressures on the Earth System are exceeding numerous local, regional, and global thresholds, with abrupt and possibly irreversible impacts upon the planet's life-support functions (United Nations Environment Programme (UNEP), 2012). Planetary boundaries provide a framework to study these phenomena, by defining a "safe operating space for humanity with respect to the Earth System" (Rockström *et al.*, 2009a). Planetary boundary studies seek to set control variable values that are a safe distance from thresholds of key biophysical processes governing the planet's self-regulation to maintain conditions conducive to life (Rockström *et al.*, 2009b). This builds upon landmark efforts by Meadows *et al.* (1972) to first define global limits to growth. Their prediction that key resource scarcities would emerge has proven remarkably accurate (Turner, 2008), albeit delayed – but not avoided – through the advent of computer technology. Ecological and economic warnings since at least Malthus have called attention to economies' dependence upon natural resources. The observation that near-exponential growth of human population and economic activity cannot be sustained, far from being disproven, is more valid than ever (Brown *et al.*, 2011). Those who deny limits to growth are unaware of biological realities (Vitousek *et al.*, 1986).

The initial planetary boundary exercise identified nine global-scale processes, including climate change, rate of biodiversity loss (terrestrial and marine), nitrogen and phosphorus cycles, ozone depletion, ocean acidification, freshwater, land use change, chemical pollution, and atmospheric aerosol loading (Figure 1). Preliminary safe planetary thresholds were established for seven of these, and three – rate of biodiversity loss, climate change, and the nitrogen cycle – were found to have already surpassed such a threshold (Rockström *et al.*, 2009a). Many such changes occur in a nonlinear, abrupt manner; others are more incremental and subtle. Yet both types of change threaten the viability of contemporary human societies by diminishing or destroying ecological life-support systems. If one or more of these boundaries are crossed, it could be "deleterious or even catastrophic" as nonlinear, abrupt environmental change occurs at the continental to planetary scale (Rockström *et al.*, 2009b).

Here an ecologically rich revision to the planetary boundary framework is proposed – in the tradition of political ecology, not ignoring politics – to set the threshold of how

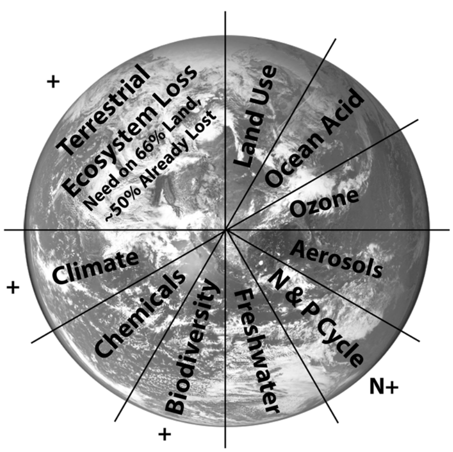


Figure 1.
Proposing a terrestrial ecosystem loss planetary boundary

many intact terrestrial ecosystems are required to sustain the biosphere. It is not possible to carry out controlled experiments upon our one biosphere to know at what point collapse occurs. We are thus left with observational studies and synthesis papers regarding what is known about ecosystem collapse at other scales. This paper first reviews what is known about biodiversity and old-growth forest loss, abrupt climate change, and ecosystem collapse as ecological systems are diminished at lesser scales. Next, the critical phase shift seen as landscapes percolate from nature surrounding humanity, to small reserves surrounded by human works, is presented as analogous to outcomes for the biosphere, whose terrestrial ecosystems are after all simply a large-scale landscape.

The remainder of the paper synthesizes these findings regarding ecosystem loss and thresholds in loss of ecosystem connectivity into a rationale for recognition of a tenth planetary boundary in regard to terrestrial ecosystem loss. It is suggested that some two-thirds of Earth's land surface should be protected totally (44 percent) or partially (another 22 percent) to avoid biosphere collapse. Given current best estimates are that approximately one-half of Earth's terrestrial ecosystems have already been lost, the discussion centers around biocentric policy measures required to protect and restore terrestrial ecosystem connectivity in order to maintain global ecological sustainability.

Currently nine planetary systems are recognized as providing a safe operating space for humanity, as long as boundaries are not exceeded. It is thought three systems (denoted with +) have already surpassed their boundaries. This paper proposes a terrestrial ecosystem boundary of 66 percent ecosystem land cover (44 percent as intact natural ecosystems and 22 percent as agro-ecological buffers) to avoid biosphere collapse. Best estimates are that about 50 percent of terrestrial ecosystems have been lost; thus this boundary has been surpassed too, albeit full impacts may not yet be realized due to time lags (adapted from Rockström *et al.*, 2009a).

Setting boundaries requires normative decisions on risk and uncertainty. Planetary boundary details and methodology are not without critics, as they are in themselves an imperfect social construct, prone toward bias and political boundaries favoring the rich. Setting thresholds may itself prolong the risk of continued degradation, falsely implying that there is time and it is safe to delay action (Schlesinger, 2009). Yet there is no escaping the observation that humans have become a powerful agent in Earth System evolution (Biermann, 2012). Given the well-documented plethora of environmental decline, there is little question that carefully quantifying when these changes become dangerous (specifying uncertainties) and what can be done to avoid possible human extinction and biosphere collapse remains a valuable field of inquiry. Civilization depends upon humanity remaining within thresholds (Folke *et al.*, 2011).

This study takes a whole-system approach to studying the needs of the Earth System. The Gaia hypothesis holds that the Earth System is in some ways analogous to a living, self-regulating organism – with air, land, soil, and oceans as her organs; plants and animals as cells; and water as blood, cycling nutrients and energy to sustain life. Formulated by James Lovelock (1979), the Gaia hypothesis noted the role of biology in promoting homeostasis in the Earth System; that is, life maintains the conditions for life. Coordinated activity between species and the environment is similar to interactions between cells and organs in multicellular organisms (Kondrat'ev *et al.*, 2001).

Earth has gone through many changes. The last 10,000 years of the Holocene epoch has been an unusual period of stability, with temperature, freshwater, and biogeochemical flows staying in a relatively narrow range. It is increasingly acknowledged that human activities, including use of fossil fuel and industrial agriculture, are destroying ecosystems and changing the climate, threatening this stability. A growing human population extracts goods and services from the Earth System at a rate that erodes its capacity to support us (Steffen *et al.*, 2011). Humanity's deleterious effects upon ecosystems have clearly become a force of nature, impacting Earth System functioning and threatening this stability (Zalasiewicz *et al.*, 2011).

Some have proposed that human dominance signals a new geological epoch that could supplant the Holocene; it has been dubbed the Anthropocene (Crutzen, 2002; Steffen *et al.*, 2011). As we move further into the Anthropocene, humanity risks driving the Earth into "hostile states from which we cannot easily return" (Steffen *et al.*, 2011). Humans depend upon the biosphere – the global Earth System integrating life with its environment – for the human life-support system. Human development and advancement are often not perceived as being connected with the biosphere and ecosystem services. Given human domination of the biosphere, ecology must account for human behavior (Peterson, 2000).

Recently a group of ecological and development luminaries called the Blue Planet Laureates (Brundtland *et al.*, 2012) noted the almost certain impossibility of achieving global ecological sustainability without addressing related issues of poverty, inequity, and injustice, noting that infinite growth on a finite planet is not possible. Kosoy *et al.* (2012) go so far as to say the dominant economic system, stressing industrial growth, is delusional, not acknowledging that economies must live within Earth's biogeochemical constraints and that human system growth accumulates ecological debt. Industrial capitalism has not been systematically reviewed in light of 200 years of science. This economic model is based upon a mechanistic worldview that destroys its own life-support system through failure to see the essence of interrelated social and ecological systems (Taylor and Taylor, 2007), as all growth-based development is ultimately unsustainable (Daly, 2005).

Political ecology seeks to integrate natural and social science approaches to understanding the relationship between ecosystems and people (Peterson, 2000). Political ecology is firmly rooted in geography and first emerged in the 1970s to link community ecology, cybernetics, systems theory, and cultural adaptation to address ecology and political economy concerns. Political ecology has been accused of lacking ecology (Walker, 2005). Here I propose an ecologically rich revision to the planetary boundary framework – while not ignoring politics – necessary to sustain terrestrial ecosystems, and thus the biosphere, in order to maximize all life's well-being. Planetary boundary thought presently lacks a terrestrial ecosystem boundary and is anthropocentric, in essence writing off other life forms that don't keep humanity "safe." It is suggested that planetary boundary studies must seek to determine thresholds to maintain all life, including the biosphere as a whole.

Biodiversity and old-growth forest loss, abrupt climate change, and ecosystem collapse

Humanity dominates the Earth to such an extent that an unknown potential exists for Earth to shift rapidly and irreversibly into a previously unknown state (Barnosky *et al.*, 2012). Humanity faces the enormous challenge of meeting human needs while maintaining the biosphere's ability to provide food, freshwater, forest resources, and a relatively stable climate in the long run (Foley *et al.*, 2005). Agriculture, forestry, and urbanization are transforming biogeochemical cycles, changing global climate and the structure and function of terrestrial ecosystems.

There have been various attempts to quantify human impacts upon the global ecological system. Some one-third to one-half of global ecosystem production is now used by humans, and agricultural systems by various estimates now cover 40-50 percent of the land surface (Foley *et al.*, 2005; Mooney *et al.*, 2009). Human appropriation of the net primary productivity of Earth's terrestrial ecosystems has been estimated to be 23.8 percent, with some 53 percent of this harvest for use, 40 percent due to land-use productivity changes, and 7 percent the result of human-caused fires (Haberl *et al.*, 2007). An earlier estimate placed human use of Earth's biological production at 50 percent (Vitousek *et al.*, 1997).

Forests today cover some 30 percent of the Earth's land surface, storing some 45 percent of terrestrial carbon (Bonan, 2008). Deforestation comprises the cutting, clearing, and removal of forest and its conversion into anthropogenic ecosystems such as pasture or cropland (Kricher, 1997). Humans have altered the terrestrial biosphere for some 8,000 years, yet the destruction has intensified over the past century, estimated by some to have crossed a critical threshold with 50 percent of the terrestrial biosphere transformed to anthropocentric non-natural systems by the mid-twentieth century.

Around half of the world's three billion hectares (ha) of forests prior to significant human impact has been deforested over the past 80 centuries (Bryant and Bailey, 1997). Williams (2003) sets the parameters of possible annual deforestation rates between 7.5 and 20 million ha per year. During the 1990s clearance of tropical forests was as high as 152,000 km^2 annually (Bonan, 2008). While about half of the world's original forests remain, most have been heavily impacted by humans and can no longer be considered old-growth forests. As of 2000, various estimates are that 29-75 percent of nature has been lost to land-use changes (Ellis, 2010).

Estimates are that less than one-fifth of Earth's original forests remain in large, relatively intact natural primary ecosystems (Bryant *et al.*, 1997). Conversion of forests and other natural ecosystems to agriculture, averaging 0.8 percent annually over the past 40-50 years, is the major force reducing terrestrial ecosystems (Millennium Ecosystem Assessment, 2005). Some 70 percent of the land that was deforested was changed to agricultural land (United Nations Environment Programme, 2002). Most existing protected areas are small, isolated, and fragmented (Soulé and Terborgh, 1999a). At current persistent rates of deforestation, tropical forests will not remain outside protected areas 35 years from now (Terborgh and van Schaik, 1997).

Large, connected primary and old-growth forests maintain ecological and evolutionary patterns and processes while providing ecosystem services that make the planet habitable (Ehrlich and Ehrlich, 1981; Noss and Cooperrider, 1994). Ecosystem functions include nutrient cycling and energy flows, disturbance regimes and recovery processes (succession), hydrological cycles, soil formation, weathering and erosion, decomposition, herbivory, predation, pollination, seed and animal dispersal, plant biomass production, and drought resistance (Noss, 1992; Kareiva and Marvier, 2003).

Fragmentation results when a single forest is divided into a number of smaller habitat patches, and fragmentation, habitat loss, and degradation are major sources of decline in biodiversity and ecosystem functionality (Ehrlich and Ehrlich, 1981; Diamond, 1984; Wilson, 1985; Soulé, 1991; Noss and Cooperrider, 1994). Forest fragmentation leads to significant changes in ecological conditions. Some changes are abiotic: patches tend to be drier and more prone to windthrows. Others are biotic: forest fragments have fewer forest interior species and are more likely to undergo invasion by exotic weedy species. Fragmentation also reduces forests' capacity to sequester carbon (Dobson *et al.*, 1999). Habitat fragmentation in conjunction with climate change causes elevated tree mortality along forest edges, altering canopy dynamics, community composition, biomass accumulation, and carbon storage (Laurance, 2004).

Large core protected areas, configured to minimize edge effects and maximize interior habitat, are critical to maintaining landscapes where nature remains the matrix, providing top-down ecological constraint upon ecosystem pattern and process (Soulé and Terborgh, 1999a; Noss *et al.*, 1999). Recent findings indicate that edge effects can increase in fragmented forests through continuous diminishment even with relatively little new loss of habitat (Riitters and Wickham, 2012).

Widespread loss of biodiversity could diminish the Earth System's ability to regulate key biological processes and feedbacks (Steffen *et al.*, 2011). The richness of species found in ecosystems gives resilience to ecosystem processes (Rockström *et al.*, 2009a). There is growing evidence that biodiversity keeps ecosystems from tipping into undesired states (Folke *et al.*, 2004). Species loss affects the functioning of remaining species and their response and adaptation to changing conditions (Rockström *et al.*, 2009b). Species extinction rates already exceed background rates by 100-1,000 times what has been typical over Earth's history (Millennium Ecosystem Assessment, 2005).

Wildlife corridors maintain connectivity across scales and can offset habitat fragmentation (Jones *et al.*, 2012). Connectivity is essentially the opposite of fragmentation. Corridors preserve existing connections (Noss and Cooperrider, 1994). Connectivity is a complex topic, varying from species to species and their ability to disperse as well as across scales. Retaining habitat connectivity can stimulate recolonization of habitat core areas following local extirpation, allow for daily and seasonal movements and normal dispersal of animals, and alleviate impacts of habitat fragmentation (Dobson *et al.*, 1999; Schumaker, 1996). Normal flows of energy, water, and nutrients – as well as natural regeneration of disturbed ecosystem patches – occur in connected landscapes.

Where ecological connectivity is lost, it can be restored. This approach has been called "rewilding" (Soulé and Noss, 1998). Soulé and Terborgh (1999a, b) argue that the restoration of connectivity must be a ubiquitous conservation activity in both temperate and tropical regions and must focus upon large-scale, top-down processes such as those provided by keystone species. It has been shown that tropical forests show remarkable resilience, and once land-use pressures destroying and diminishing them are reduced, they can recover relatively rapidly (Bhagwat *et al.*, 2012), though incompletely if critical thresholds in composition, structure, function, and dynamics have been surpassed.

Large old trees often play critical ecosystem roles, storing carbon, cycling water, providing food to wildlife, and otherwise supplying rich microenvironments. They are rapidly declining worldwide, being logged and facing elevated mortality and reduced recruitment (Vieira *et al.*, 2005). By themselves, large trees also increase landscape connectivity by attracting seed dispersers and pollinators and providing steppingstones across a landscape (Lindenmayer *et al.*, 2012). The loss of large-bodied wildlife, also termed apex consumers, cascades through ecosystems worldwide and may be humanity's most pervasive impact upon the natural world. Loss of keystone species has led to simplified and destabilized ecological networks and connectivity patterns (Barnosky *et al.*, 2011). Loss of apex consumers shortens food chains and alters the intensity of herbivory and thus plant abundance and composition. As top-down forcing is lost, ecosystem regime shift often occurs (Estes *et al.*, 2011).

Primary and old-growth forests are irreplaceable for sustaining tropical biodiversity, which requires well protected areas and curtailed demand for old-growth timber

(Gibson *et al.*, 2011). Primary tropical forests transpire large amounts of water, cooling microclimates, bioregions, and the planet. Changes in forest cover both cause and result from changes in climate, as vegetation cover is tightly coupled to Earth's climate through biogeophysical feedbacks (Brovkin *et al.*, 2009). As well as storing large amounts of carbon dioxide (CO_2) in trees, old-growth forests continue removing CO_2 from the atmosphere and accumulating it in biomass and soils (Luyssaert *et al.*, 2008).

Agriculture has driven much primary forest loss, and agricultural expansion into intact terrestrial ecosystems must end (Foley *et al.*, 2011). However, the processes driving primary tropical forest deforestation and diminishment have shown a recent shift toward major industries (rather than poor farmers) such as commercial-scale logging, oil and gas, mining, and plantations as the more frequent cause of forest loss (Butler and Laurance, 2008).

As tropical deforestation quickens, protected areas are often the only places where natural ecosystems and biodiversity can persist. Yet protected areas in the tropics are especially vulnerable to human encroachment and other environmental stresses. Laurance *et al.* (2012) found that about half of tropical reserves are losing biodiversity across taxonomic and functional groupings, and 80 percent of reserves show signs of decline. Often this was due to threats to landscapes around reserves, absence or small size of buffers and transition zones, and lack of connectivity with the broader landscape.

Convincing evidence argues that industrial logging in tropical forests cannot be both ecologically sustainable and profitable (Zimmerman and Kormos, 2012). There are questions whether repeated harvests can be taken while sustaining natural forest ecosystems' full range of ecological processes and patterns (Nasi and Frost, 2009). International efforts to protect the world's forests are made more difficult by a lax definition of forests, equating primary and old-growth forests with tree plantations and heavily managed natural forests, which are quite distinct ecologically (Sasaki and Putz, 2009). It is likely that existing primary and other old-growth forests must be fully protected and expanded if the biosphere is to be maintained.

Recently much research has studied catastrophic state shifts in ecosystems and the conditions under which such shifts occur. It is believed that some complex ecosystems can exist in alternative stable states. Shifts between states can cause large losses in ecosystem patterns and processes, including an end to economic benefits (Scheffer *et al.*, 2001). Globally, large areas that once housed natural biodiversity and ecosystems which power the Earth System now contain only a few species (Barnosky *et al.*, 2012).

Human activities can potentially push the Earth System past tipping points into different qualitative states (Lenton *et al.*, 2008). Recent efforts to determine early warning signals for such critical state transitions have noted generic aspects of an ecosystem approaching a critical point and undergoing phase shift: bifurcations, flickering between states, critical slowdown in system processes, and autocorrelation in these processes (Drake and Griffen, 2010; Carpenter *et al.*, 2011; Scheffer *et al.*, 2009).

Knowing that critical thresholds are near or have been crossed is complicated by lag times; thus, it cannot be clear, except in retrospect, whether an ecosystem or even the entire biosphere has crossed a critical transition (Barnosky *et al.*, 2011). There may be no warning of such a shift, since drastic changes can appear in nature abruptly (Hastings and Wysham, 2010). Underlying drivers that push ecosystems toward thresholds must be slowed and addressed well before thresholds are reached, yet indicators of ecosystem regime shift are often detected too late (Biggs *et al.*, 2009).

There is strong consensus that human activities are influencing the Earth's climate (International Panel on Climate Change, 2007), and growing concern that science has consistently underestimated its rate and intensity. Rahmstorf *et al.* (2007), comparing IPCC's Third Assessment Report with subsequent observations, found that the IPCC had underestimated change in global mean temperature, sea level rise, and atmospheric CO_2 concentration. Hansen *et al.* (2012) found that extreme heat during the summertime is occurring at three times the standard deviation of historical climatology, with extreme heat anomalies, e.g. in the American southwest in 2011 and Moscow in 2010, having gone from covering 1 to 10 percent of Earth's surface at any time. They compare the increased probability of such events to "loaded dice."

Climate change is often perceived as a smooth, gradual process, when in fact it could pass tipping points and become abrupt and potentially runaway (Lenton *et al.*, 2008). We are witnessing long-term and abrupt climate changes already in Arctic sea ice melt, ice mass loss in Greenland and West Antarctica, a shift of subtropical regions toward the poles, bleaching and death of coral reefs, large floods, weakening of the ocean carbon sink (Rockström *et al.*, 2009b), and more frequent extreme weather events (Hansen *et al.*, 2012). Impacts of human climate forcing may be "big, fast, and patchy" at a regional scale, triggering abrupt crashes of ecosystems (Breshears *et al.*, 2011).

It is generally accepted that given a climate sensitivity of about 3°C for doubled CO_2 equivalency, atmospheric concentration of CO_2 must be reduced from its current almost 400 to 350 ppmv, to maintain the relative Holocene climate stability within which civilization has evolved (Hansen *et al.*, 2008). To maintain such an Earth System, it is critically important to rapidly reduce fossil fuel emissions (Hansen and Sato, 2011). Recovering from present overshoot would require the phasing out of coal, an end to all fossil fuels unless carbon is sequestered, protecting old-growth, and use of agriculture and forest practices to resequester carbon (Hansen *et al.*, 2008). It has been suggested that slowing population growth could account for 19-29 percent of the emissions reductions necessary by 2050 to avoid the most dangerous impacts of climate change (O'Neill *et al.*, 2010).

Climate change threatens all levels of biodiversity (Maclean and Wilson, 2011), causing changes in vegetation communities large enough to impact the integrity of biomes and hasten a sixth mass extinction (Bellard *et al.*, 2012). Malcolm *et al.* (2006) consider global warming to be one of the most serious threats to biodiversity, and losses of 39-43 percent of endemic species from 25 major biodiversity hotspots to be possible. Synergistic climate and vegetational changes are likely to induce profound shifts in the societies living there (Heyder *et al.*, 2011). It is difficult to predict with certainty how terrestrial ecosystems will interact with other global environmental changes, though it is evident they will be simpler structurally, with more early successional vegetation (Walker and Steffen, 1997).

By the end of the century we can expect virtually all ecoregions to be under climate stress caused by heat and precipitation patterns well outside recent variability. Climate change has been found to impact biological systems – and their phenology, distribution of species, morphology, and net primary productivity – including the "Global 200" ecoregions of exceptional biodiversity (Rosenzweig *et al.*, 2008; Olson and Dinerstein, 2002). Terrestrial ecosystems cycle ten times the annual amount of carbon released by fossil fuels and altered land use; climate change may severely impede these processes, restructuring the terrestrial biosphere at continental scales (Heyder *et al.*, 2011). Tropical forests in particular are vulnerable to a warmer, drier climate (Bonan, 2008). Ecosystems exert influence upon climate through changes in the water, energy, and greenhouse gas balance (Chapin *et al.*, 2008).

Climate change affects forests by altering the frequency, timing, duration, and intensity of naturally occurring disturbance patterns including fires, drought, insects and pathogens, introduced species, hurricanes, and extreme weather (Dale *et al.*, 2001). Shifts in precipitation patterns associated with climate change are expected to intensify droughts, damaging and causing further decline in forests (Choat *et al.*, 2012). Some studies have shown that forest cover plays a far greater role in determining rainfall than previously known (Sheil and Murdiyarso, 2009). Largely as a result of drought, the Amazon rainforest, facing climate change – induced extreme warming and drying, may possibly die back to refugia, releasing CO_2 in a massive positive feedback (Cox *et al.*, 2004; Nepstad *et al.*, 2008).

Human land-use changes likely increase the vulnerability of tropical forests to climate change and may be as important as abiotic changes in their decline, as synergies magnify habitat loss and fragmentation (Brodie *et al.*, 2012). To allow vegetation to adapt to climate change, it is important to maintain and enhance landscape connectivity so species can migrate. Protected areas should be identified both because they would allow biodiversity and ecosystems to migrate and otherwise adjust to climate change, and because their vegetation is important for minimizing warming (Hannah *et al.*, 2007).

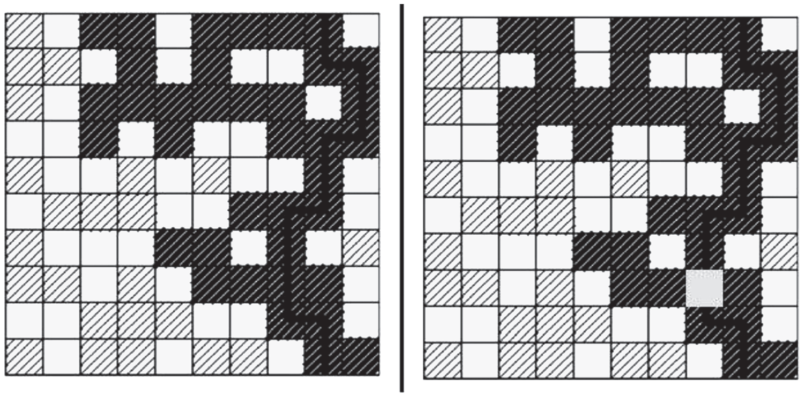
Percolation theory and landscape connectivity

One approach to studying the effects of habitat loss and fragmentation upon landscapes has been percolation theory, which shows that many aspects of habitat fragmentation change rapidly below critical levels of habitat loss (Swift and Hannon, 2010). As 40 percent of a landscape's habitat is lost, many linear landscape measures such as connectivity, edge density, contagion, distance to nearest neighbor, and fractal dimension show a 50 percent probability of an abrupt change to nonlinear responses (Hargis *et al.*, 1998). As habitats are dissected into smaller parcels, landscape connectivity – the functional linkage between habitat patches – becomes disrupted (With and Crist, 1995).

A percolating cluster is characterized by a path of habitat cells across a landscape from one side to the other, regardless of scale, enabling organisms – as well as flows of energy, water, nutrients, and other materials – to move from one edge of the landscape to the other. Percolation models that simulate landscapes have found that when habitat covers <59 percent (0.59275) of the landscape (regardless of scale); the largest habitat patch decreases abruptly and no longer spans the entire landscape (Gustafson and Parker, 1992; Andren, 1994; Bascompte and Sole, 1996). When connectivity is defined on the basis of the nearest neighbor, a critical threshold exists near 60 percent whereby the probability of a percolating cluster is 50 percent. Below this level percolating clusters rarely exist, and even 2 percent past above this threshold the likelihood of fragmentation becomes very high (Williams and Snyder, 2005) (Figure 2).

Other landscape metrics of interest to landscape connectivity that may have implications for sustaining the global biosphere's terrestrial ecosystems include: at about 40 percent of habitat retention (60 percent loss), the distance between patches increases rapidly (Gustafson and Parker, 1992; Andren, 1994), and at 30 percent retention, habitat patch numbers peak. These fragmentation thresholds may signal a positive feedback mechanism with potential to drive irreversible regime shift in ecosystem functions across fragmented landscapes (Pardini *et al.*, 2010).

When a percolating cluster exists, the landscape is connected and characterized by a few large habitats, which surround non-habitat. Below this threshold of ~ 59 percent the landscape is characterized by many small and disconnected habitats, encompassed



Notes: On the left, a 10 × 10 lattice of 100 cells is shown. Sixty shaded habitat cells have been specified randomly. Dark-shaded cells constitute the percolating cluster, which under the nearest neighbor rule connect the top and bottom edge. The dark line indicates the shortest path, or backbone, through the percolating cluster. On the right, it is shown that with loss of only a single (solid gray) cell, the landscape has percolated, and no longer contains a backbone of connectivity. Note in this case loss of any cell along the backbone results in percolation. While simplified immensely, such phase shifts occur often in natural landscapes across scales as habitat is lost. Landscapes including the biosphere are percolating from connected nature surrounding humans, to humans surrounding fragmented nature (adapted from Williams and Snyder, 2005)

Figure 2.
Loss of a percolating cluster

by non-habitat. This holds across scale (Wu, 2004) and represents a direct phase shift between connectivity and non-connectivity. Below this level of connectivity, the likelihood of critical transitions increases, as transformed ecosystems can change rapidly (Barnosky *et al.*, 2011). Critically, as the landscape percolates, a landscape state shift occurs whereby connected habitats surrounding humanity switch to human works surrounding fragmented islands of habitat.

Throughout history, human endeavors and settlements were islands within the sea of natural ecosystems; now, as a result of habitat fragmentation, at most scales this has largely been reversed (Janzen, 1986), with the exception of important remaining large natural ecosystems such as the Amazon and boreal forests. This matrix of intact terrestrial ecosystems is being lost across bioregions, continents, and the global biosphere as landscapes percolate, losing connectivity and the ability to maintain top-down regulation, symbiotic health, and ecosystem services.

Investigations of continental-scale conservation have noted the importance of top-down regulation provided by intact ecological matrixes across large scales (Soulé and Noss, 1998; Soulé and Terborgh, 1999a, b). Solutions to habitat loss and fragmentation require the popular embrace and implementation of basic conservation biology principles. These include the need to protect large core areas, establish agro-ecological buffers and transition zones, and keep the large core areas connected as the matrix for sustainable human societies.

Historically, regeneration from natural disturbance occurred within a matrix of intact ecosystems, precisely what is lost when landscapes percolate to patches of natural ecosystems surrounded by humans. Viewing terrestrial ecosystems in space and time as changing patterns of patch and matrix is not scale dependent; one explicitly states the scale for which an ecosystem and landscape perspective is taken (Allen and Hoekstra, 1992). The biosphere's terrestrial ecosystems can thus be viewed as a single landscape.

Over recent decades, most governments and conservation organizations have called for 10-12 percent protection of each type of ecosystem, reducing terrestrial ecosystems to isolated, unconnected remnants in a context of human development. Some 13 percent of Earth's total land is now covered with protected areas (UNEP, 2012) – with about half providing adequate protections (Laurance *et al.*, 2012). At the 2010 Nagoya Conference on the Convention on Biological Diversity, a 17 percent protected area goal for terrestrial ecosystems was proposed (Noss *et al.*, 2012).

Achieving these targets could prove inadequate to meet human needs and may be even crash the biosphere. Targets of 10 or 17 percent appear largely arbitrary, relegating virtually all unprotected lands, particularly in the tropics, to industrial development and conceding that with up to 90 percent habitat loss, some 50 percent of species will go extinct from habitat loss alone (Soulé and Sanjayan, 1998). This level of terrestrial ecosystem protection virtually precludes a biospheric percolating cluster of global terrestrial ecosystem connectivity adequate to mediate critical ecological flows for sustainability.

Percolation theory's insights into ecological connectivity applied across scales support ambitious programs of habitat protection, not only to foster biodiversity and healthy ecosystems, but for sustainability of continents and the biosphere. Similarly, Noss *et al.* (2012) are calling for "bolder conservation," proposing that some 25-75 percent be managed for biodiversity conservation and stating bluntly that "Nature needs at least 50%, and it is time we said so." Williams (2000) urges an Earth System – based conservation ethic, based upon an "Earth narrative" of natural and human history, which seeks as its objective the "complete preservation of the Earth's biotic inheritance" to ensure biosphere sustainability.

Terrestrial ecosystem loss as a planetary boundary

It is worrying that terrestrial ecosystem loss and diminishment do not explicitly feature within the initial conception of planetary boundaries. Running (2012) attempted to explicitly define a measurable planetary boundary for terrestrial ecosystems based upon plant net primary productivity. Yet measuring biomass production may not assess critical spatial and scale-dependent processes and patterns provided by fully intact and connected natural ecosystems, for example, conflating tree plantations' biomass with old-growth forests.

What is sought here is the first iteration of a less arbitrary threshold value and precautionary boundary for terrestrial ecosystem loss. This needs to reflect the full range of ecological services provided by intact, large, and connected ecosystems and be rooted in observed phenomena related to the loss and fragmentation of habitat. A planetary boundary for terrestrial ecosystem loss would go well beyond the current planetary boundary proposal's land system change and biodiversity loss thresholds and deal with ecological processes and patterns – the integrative services – provided by land still covered with intact natural vegetation.

The original planetary boundaries developed by Rockström *et al.* (2009a, b) related to terrestrial ecosystems set a 15 percent threshold for agricultural conversion, and a biodiversity extinction rate of ten species per million per year. This current conception of a planetary boundary measuring land and natural vegetation is inadequate. It is not enough to assess the quality of land and its intact ecosystems only in terms of how much land is under agricultural development and how many species are being lost. The current land-use boundary only partially reflects the loss of ecosystem processes like pollution absorption, wildlife migration, pollination, and soil development. The biodiversity boundary does not encompass loss of ecological patterns such as naturally evolved plant communities concurrent with diminishment or disappearance of terrestrial ecosystems.

Terrestrial ecosystems are more rooted in geography than are other planetary boundaries, so a boundary must be based upon their position, connectivity, and quality. A bioregional and continental terrestrial ecosystem boundary could be measured based upon what we know about landscape pattern and percolation states at various thresholds of natural plant community coverage; and about critical thresholds, regime shifts, and different basins of attraction for ecosystems at the plant community and landscape criterion. A planetary boundary for terrestrial ecosystem loss drawing upon computerized mapped data, aggregating conditions of natural habitats across scale, would capture the full complexity of land-based ecological thresholds (Barry *et al.*, 2001).

Avoiding fragmentation and providing for core ecological areas throughout a mixed-use landscape is the challenge of terrestrial ecosystem ecology. Persistent large, connected, and naturally evolving ecosystems are a central organizing principle of a living biosphere – in fact, of life itself. Like the land-use planetary boundary, terrestrial ecosystem loss is tightly coupled with other boundaries. The spatial distribution of this loss across scales is crucial to ensuring that continental and biospheric scale land-cover thresholds are not crossed.

A new planetary boundary threshold is proposed: that 60 percent of terrestrial ecosystems must remain intact for long-term biosphere sustainability, with the boundary set at 66 percent as a precaution. This is seen as necessary to provide a safe space not only for humanity but for all life, including the Earth System itself. Ensuring that natural ecosystems and their biogeochemical flows remain the context for human endeavors is hypothesized to be a requirement to sustain the biosphere long term. Doing so requires large core ecological areas – and the critical connectivity of ecosystem processes and patterns – as the global landscape matrix.

It is further proposed on the basis of ecology's percolation theory that two-thirds of the 66 percent of terrestrial ecosystems that are to be maintained (as discussed above) must remain as ecological core areas, to ensure the ecological integrity of semi-natural agro-ecological landscapes by encompassing them within a matrix of intact nature. Thus a terrestrial ecosystem loss planetary boundary is proposed that protects 44 percent of the global land mass as intact ecological cores, with 22 percent as agro-ecological, agroforestry, and managed forest buffers and transition zones.

Buffer zones are multiple-use areas that can serve as habitat for some species and insulate core reserves from human activities (Soulé and Terborgh, 1999a). Critical to the efficacy of large ecological core protected areas are sizable buffer and transition zones around reserves, maintaining connectivity to other forest areas, and low-impact community-based land uses around reserves (Laurance *et al.*, 2012).

Agro-ecological systems, suggested here as minimally comprising 22 percent of the land mass, will have to play a part in reestablishing an ecological context and top-down ecosystem constraint upon humanity (Dalgaard *et al.*, 2003; Francis *et al.*, 2003). It is thought that agro-ecological systems that better mimic natural processes can provide limited ecosystem services while buffering core ecological areas (Ericksen *et al.*, 2009). Agriculture as now practiced has numerous harmful effects, including pollution and habitat destruction, yet there are efforts to incorporate agriculture flows more fully with the flows across landscapes of plants, animals, nutrients, and water. Long established, agroforestry is now being augmented by innovations in permaculture, organic gardening, restoration ecology, and rewilding.

Earth needs a new class of connected global ecological preserves to sustain core ecosystem processes required for an operable biosphere, regional ecological sustainability, and sustainable human advancement. These recommendations for a terrestrial ecosystem loss planetary boundary align closely with (Soulé and Sanjayan's (1998) scientific review that to represent and protect most biodiversity, particularly wide-ranging species, 50 percent habitat protection is required. Noss *et al.* (2012), also calling for 50 percent landscape protection, note the timidity of conservation targets and lament that viable populations of native species and ecosystem services are willfully not being maintained.

Humanity is near or has recently surpassed allowable terrestrial ecosystem loss within a sustainable biosphere in the mid-to-long term. Given that as much as 50 percent of Earth's biological production may already be dominated by humans (Vitousek *et al.*, 1997), and as much as 33-40 percent of biospheric production has been co-opted by humans (Vitousek *et al.*, 1986; Running, 2012), it is urgent to define the terrestrial ecosystem loss boundary. Like the climate change, biodiversity, and nitrogen cycle boundaries, humanity may have already crossed the planetary boundary for loss of terrestrial ecosystems. The key threshold is that at these levels – with 66 percent of terrestrial ecosystems arrayed across continents and the biosphere – natural and semi-natural ecosystems remain the context for human endeavors. And within this ecosystem matrix, intact core ecological reserves constitute the encompassing matrix for agro-ecological patches. The critical increase in fragmentation and reduction in habitat connectivity and ecological cores that threatens the biosphere can be avoided by maintaining nature as the context for human activities. The potential for natural ecosystems to continue their unimpeded evolutionary development based on the full array of genetic materials is also maximized.

In addition to protecting all existing natural ecosystems, there exists great potential to target the restoration of key areas on landscapes – such as critical gaps in habitat corridors to restore a percolating cluster – to improve the connectivity of a landscape or even a bioregion. Restoration ecology and rewilding activities that reestablish natural disturbance regimes and promote movement of species between habitat fragments should be emphasized (Soulé and Terborgh, 1999a). Restoring corridors between isolated habitat patches can mitigate or reverse the effects of fragmentation (Williams and Snyder, 2005), and potentially reconstitute a global percolating cluster of terrestrial ecosystems as the context for continued human and all life's well-being.

Biocentric discussion on achieving global ecological sustainability

The paper proposes that 66 percent of the Earth's land surface must be totally (44 percent) or partially protected (another 22 percent) to avoid biosphere collapse. This conclusion arises from synthesis of what is known regarding ecosystem collapse at other scales and from consideration of percolation theory applied to landscape analysis. The percentage of land area now protected (ca 13 percent) – half of it badly – results mostly from political and economic considerations. While nobody knows for sure how much of the biosphere must be kept intact, most specialists would intuit it is more than 13-17 percent.

Humanity desperately needs a predictive science of the biosphere if we are to avoid its collapse to an unknown stable and simplified state or even death (Moorcroft, 2006).

It is vital to both the biosphere and human advancement that what is known about healthy terrestrial ecology be united with a legal framework to pursue local, regional, and global sustainability goals. We must get at the keystone role that large, intact, naturally evolved ecosystems have in the function of the Earth System, as well as local well-being and regional sustainability. This paper's initial 66/44/22 percent finding for ecosystem cover, natural ecosystems, and agro-ecosystems is meant as a hypothesis to spur more investigation into quantifying terrestrial ecosystem patterns and processes necessary for continuation of a fully functional biosphere.

Science needs to accurately consider worst-case scenarios regarding continental and global-scale ecological collapse. The loss of biodiversity, ecosystems, and landscape connectivity reviewed here shows clearly that ecological collapse is occurring at spatially extensive scales. The possible collapse of the biosphere and complex life, or eventually even all life, needs to be better understood and mitigated against. Further research is needed on how much land must be maintained in a natural and agro-ecological state to meet landscape and bioregional sustainable development goals while maintaining an operable biosphere.

It is suggested that 66 percent of Earth's land mass must be maintained in terrestrial ecosystem cover to maintain critical connectivity necessary for ecosystem services across scales. Yet various indicators show that around 50 percent of Earth's terrestrial ecosystems have been lost and their services usurped by humans. The means Earth and humanity are in a state of ecological overshoot, as it is probable that more terrestrial ecosystems have been lost than the biosphere can bear.

Those knowledgeable about planetary boundaries – and abrupt climate change and terrestrial ecosystem loss in particular – must boldly insist on articulating the range and severity of possible threats of global ecosystem collapse, while proposing sufficient solutions. It is not possible to do controlled experiments on the Earth system; all we have is observation based upon science and trained intuition to diagnose the state of Earth's biosphere and to suggest sufficient remedies based on ecological science.

It is prudent not to dismiss the possibility that the Earth System – the biosphere – could die if critical thresholds are crossed. The death of cells, organisms, plant communities, wildlife populations, and whole ecosystems is seen continually in nature – extreme large-scale cases being desertification and ocean dead zones. Earth scientists need to better understand how this may happen to the biosphere. Strong life-reducing trends across biological systems and scales heighten the need for a rigorous research agenda to understand at what point the biosphere may be threatened. We need better understanding of the key variables and thresholds to life's continuation and of the configuration of ecosystems and other boundary conditions sufficient to preserve the biosphere as shared habitat for all life forever. If science is to serve policy, this quest for knowledge must not be impeded by political considerations of what is feasible.

Humanity's well-being depends upon complex ecosystems that support life on our planet, yet we are consuming the biophysical foundation of civilization. Planetary boundaries have been largely anthropocentric, stressing human safety and discounting other species and the biosphere's needs beyond providing services to humans. Planetary boundaries need to be set that, while including human needs, go beyond them to include the needs of ecosystems with all their constituent species and their aggregation into a living biosphere. Planetary boundary science needs to be more biocentric.

Efforts are few that systematically assess the long-term, aggregate impact of human activities upon environmental life support systems (Kosoy *et al.*, 2012). We risk entering a series of escalating crises culminating in collapse. Possibly, as a result of degraded ecosystems, inequitable overpopulation, and resource shortages, we may witness collapse of the world socio-political-economic system (Taylor and Taylor, 2007), some sort of biosphere collapse, and perhaps death of the Earth System. There exists a need for courageous leaders to speak the difficult truths, and for all to educate and act on these matters (Cairns, 2010).

Much-needed dialogue is beginning to focus on the prospect of systemic social and ecological collapse and what sort of community resilience is possible. Ecologically mediated periods of societal collapse have stemmed from human damage to ecosystems in the past (Kuecker and Hall, 2011). What is different now is that the human species may have the scale and prowess to pull down the biosphere also.

Political ecologists must address both legal regulatory measures, as well as revolutionary processes of social change, which may establish the social norms necessary to maintain the biosphere. Rockström *et al.* (2009b) refer to the need for "novel and adaptive governance" without using the word revolution. Scientists need to take greater latitude in proposing solutions that lie outside the current political paradigms and sovereign powers.

Even the Blue Planet Laureates' remarkable analysis (Brundtland *et al.*, 2012), which notes the potential for climate change, ecosystem loss, and inequitable development patterns, neither states nor investigates the potential for global ecosystem collapse, nor does it discuss revolutionary responses. UNEP (2012) notes that abrupt and irreversible ecological change may impact life-support systems but addresses neither the profound human and ecological implications of biosphere collapse nor the full range of sociopolitical responses to such predictions. More scientific investigations are needed regarding alternative governing structures optimal for pursuit and achievement of bioregional, continental, and global sustainability if we are to maintain a fully operable biosphere forever. An economic system based upon endless growth that views ecosystems primarily as resources to be consumed cannot exist for long without total social, economic, and ecological collapse.

Planetary boundaries pose a difficult challenge for global governance, especially since burgeoning scientific insight does not seem to be enough to trigger international action to sustain ecosystems (Galaz *et al.*, 2012). It is desirable that the current political and economic systems should reform themselves to be ecologically sustainable, establishing laws and institutions for doing so. Yet current politics and economics are not sacrosanct, particularly if they are collapsing the biosphere. By not considering revolutionary change, we dismiss all options outside the dominant growth-based oligarchies.

One possible revolutionary solution to the critical issues of terrestrial ecosystem loss and abrupt climate change is a massive and global program to protect and restore natural ecosystems – funded by a carbon tax, furthering the essential reduction of fossil fuel emissions. This program would establish and protect large and connected core ecological areas, buffers, and agro-ecological transition zones throughout all of Earth's bioregions.

Global ecological sustainability depends critically upon maintaining connectivity of ecosystem processes and patterns. We simply must learn to live in a manner that does not destroy our habitat and to consider the land around us and the life and processes it sustains as a measure of societal and biospheric well-being. Political ecology has the potential to provide the needed framework to integrate human needs for just, equitable advancement with the needs of the biosphere, avoiding ecosystem collapse, and to formulate the policies and political structures required to do so.

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Further reading

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