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Key Points:
- A globally consistent framework is needed for sustainability decision making
- The framework would facilitate decision making from global-to-local and vice versa
- The framework would link multiple Earth system processes and targets

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Sustaining ecosystem services: Overcoming the dilemma posed by local actions and planetary boundaries

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Abstract Resolving challenges related to the sustainability of natural capital and ecosystem services is an urgent issue. No roadmap on reaching sustainability exists; and the kind of sustainable land use required in a world that acknowledges both multiple environmental boundaries and local human well-being presents a quandary. In this commentary, we argue that a new globally consistent and expandable systems-analytical framework is needed to guide and facilitate decision making on sustainability from the planetary to the local level, and vice versa. This framework would strive to link a multitude of Earth system processes and targets; it would give preference to systemic insight over data complexity through being highly explicit in spatiotemporal terms. Its strength would lie in its ability to help scientists uncover and explore potential, and even unexpected, interactions between Earth's subsystems with planetary environmental boundaries and socioeconomic constraints coming into play. Equally importantly, such a framework would allow countries such as Brazil, a case study in this commentary, to understand domestic or even local sustainability measures within a global perspective and to optimize them accordingly.

1. Introduction

What was once fiercely fought for by radical environmental non-governmental organizations (NGOs) has now become a matter of consensus in the academic world—namely, the recognition that human life is dependent on Earth's ecosystems and the services they provide [*Scholes et al*., 2005]. Moreover, the forebodings that such NGOs had about human beings pushing the limits of their environmental support systems have proved correct. In aggregate and at the global scale, anthropogenic pressure on ecosystems has forced the Earth system beyond a number of safe boundaries for humanity and into unknown territory, leading to levels of climatic and environmental perturbation that are unprecedented in human history [*Rockström et al*., 2009; *Barnorsky et al*., 2012; *Lewis*, 2012; *Griggs et al*., 2013].

The conversion of natural ecosystems for societal uses, such as agricultural activities for biomass production and harvest, is the second largest cause of human-induced climate change, accounting for about 10% of anthropogenic carbon dioxide (CO_2) emissions in 2011 [*GCP*, 2012]. The contribution of emissions from land use and land-use change (LUC) to total anthropogenic CO_2 emissions has been declining continuously—from about 33% in the 1960s to 20% in the 1990s [*GCP*, 2012]. Nevertheless, the conversion of natural ecosystems for biomass production, especially when unsupported by appropriate protection measures, is the single most important driver of species extinction globally [*Strassburg et al*., 2010]. Human impact on ecosystems and the appropriation of ecosystems for biomass production have reached an all-time high, amounting to about 25% of potential net primary production at the turn of the millennium [*Haberl et al*., 2007; *Erb et al*., 2012; *Running*, 2012]. Moreover, agricultural production, a key driver of greenhouse gas (GHG) emissions from forest and savanna conversion and from other LUCs, is expected to grow as human population grows, lifestyles change, and the demand for food, feed, fiber, and fuel increases [*Foley et al*., 2011; *Lambin and Meyfroidt*, 2011; *Knoke et al*., 2012]. Intensification of land use, if not accompanied by conservation practices, may lead to disruptions of the nitrogen and other biogeochemical cycles, an acceleration of phosphorus depletion, reduction in biodiversity, and ultimately a loss of ecosystem services [*Cordell and White*, 2011; *Schneiders et al*., 2012; *Austin et al*., 2013].

In spite of major academic and policy initiatives such as the Millennium Ecosystem Assessment (MEA), The Economics of Ecosystems and Biodiversity (TEEB), and the Intergovernmental Platform on Biodiversity and Ecosystem Services (IPBES), no solutions have been put in place to inform international climate negotiations on sustaining natural capital and ecosystem services [*Daily et al*., 2009; *Burkhard et al*., 2012]. Also unresolved is the question concerning the type of LUC, including land-cover changes, that will prove sustainable and capable of addressing human well-being in an environmentally constrained world [*Smith et al*., 2013]. A roadmap for sustainable land use is urgently required [*Beddington et al*., 2012; *Ehrlich et al*., 2012; *Jonas and Ometto*, 2012].

To address these challenges, we argue that a new globally consistent and expandable systems-analytical framework is needed now: (i) to provide systemic guidance for sustainability research and action across scales, and (ii) to trace and systemize impacts from the planetary to the local level, and vice versa [*Andelman*, 2012; *Rogelj*, 2013]. This framework would not only seek to constrain anthropogenic emissions from fossil fuels and the LUC sector, but would also reflect the fostering of biodiversity (as an auxiliary key indicator for safeguarding ecosystem functioning) within an expanded systems view — a view that strives to link a multitude of Earth system cycles and processes by giving preference to systemic insight over data complexity through being highly explicit in spatiotemporal terms. This framework would thus account for: (i) sustainable land use based on multiple environmental criteria, e.g., biodiversity, carbon, nitrogen, phosphorus, and water, and (ii) the multipurpose use of ecosystems. The systems approach would recognize the constraints believed to be known and suggested by the planetary environmental boundaries as delineating the "safe operating space" for humanity [*Rockström et al*., 2009] as well as the global socioeconomic conditions and limitations needed to secure a sustainable habitat and ecosystem services for the well-being of a population of 8–10 billion by 2050 [*Foley et al*., 2011; *Ehrlich et al*., 2012]. The framework would allow local/regional or national sustainability practices to be factored into a global roadmap, thereby furthering understanding of the significance of such practices when aggregated at the global scale.

We discuss the functionality of the framework and its application to Brazil, our case study, which is, like other regions (high-latitude permafrost, arid continental, and mountainous), a crucial one from a biodiversity-ecosystems point of view. This case study is an LUC and a socioeconomic hotspot. It provides insights into the challenges involved in coordinating pro-sustainability actions at the local, national, and global scales. It shows that sustainability policies must be implemented at the local and national levels with beneficiaries and policy actors being permitted to address their own relevant domestic issues directly [*Gardner et al*., 2013]. It also shows that, in the absence of a global framework, countries are finding it difficult to coordinate their environmental and socioeconomic challenges in a globally consistent way, which comes as an additional challenge to producing an overarching framework. Because of the increased openness of economies and the integration of those economies within a global market, sustainability cannot just be achieved domestically; it must also be the result of a concerted global effort. Moreover, given that countries address sustainability and environmental boundaries differently depending on their social and ecological circumstances, it is important to ensure that the aggregated impact of all country practices undertaken does not overstep planetary environmental boundaries at the global level. A new sustainability framework must also support integrated multiscale modeling to trace the coupling and cascading of feedbacks and critical systems behaviors (transitions, state shifts, global-scale spillovers from regional shocks, etc.) across scales from local to global, and vice versa [*Lambin and Meyfroidt*, 2011; *Rietkerk et al*., 2011; *Barnorsky et al*., 2012; *Liu et al*., 2013].

This commentary discusses in greater detail: (i) the challenges of setting up a globally consistent and expandable systems-analytical framework and (ii) the challenge that countries such as Brazil are facing as they seek to understand how their own domestic sustainability actions would fit into such a framework, while—given the need for Brazil, due to its own scale-specific expertise, to work at its own national/regional level—also contributing to improving the overall framework. The purpose of this discussion is to infer the research needed to balance local actions and planetary boundaries in order to foster sustainable ecosystem functioning.

2. The Need for a New Globally Consistent and Expandable Systems-Analytical Framework

Since their inception, climate treaty negotiations have set out to stabilize Earth's climate by implementing mechanisms that reduce global GHG emissions and lead to sustainable management of the atmosphere at a "safe" steady-state level (assumed to hold for an increase in global average temperature of below 2°C above preindustrial levels). In recent years, international climate policy has taken a step beyond achieving GHG concentration-related objectives by increasingly focusing on limiting temperature rise [*Rogelj et al*., 2011]. The idea of limiting cumulative global GHG emissions by adhering to a long-term global warming target was first discussed broadly and publicly by policymakers at the 2009 United Nations climate change conference in Copenhagen. It appears to be a promising and robust methodology [*Allen et al*., 2009; *Matthews et al*., 2009; *Meinshausen et al*., 2009; *WBGU*, 2009; *Zickfeld et al*., 2009; *Raupach et al*., 2011]. To comply with it, the emission reductions required from the fossil-fuel and land-use sector are daunting: 50%–85% below the 1990 global annual emissions, with even greater reductions for industrialized countries [*Fisher et al*., 2007; *Jonas et al*., 2010, 2014]. The underlying assumptions are equally daunting: terrestrial or oceanic sinks continuing to offset fossil-fuel and LUC emissions before achieving an emissions balance that goes beyond CO_2-C (i.e., CO_2-equivalents and also including CH_4, N_2O, etc.), with no systemic surprises occurring during the transition process.

The emissions-temperature example resulting from the cumulative emissions approach can serve as a first example for our framework: one that will allow any country to understand its national and short-term mitigation and adaptation strategies, including target emissions, in a globally consistent and long-term emissions-temperature context. Using this approach, cumulative emissions are constrained and globally binding and even exhibit quantitative uncertainty (i.e., they can be estimated only imprecisely); and whether or not compliance with an agreed temperature target will be achieved is also uncertain. In this context, total uncertainty is understood more widely than usual, as it combines diagnostic uncertainty (looking back in time) and prognostic uncertainty (looking forward in time) to reach the future temperature target [*Jonas et al*., 2014]. However, this example requires further discussion.

The concept of reducing fossil-fuel emissions and analyzing their path dependencies is considered preferable to the concept of constraining cumulative emissions. One widely stated argument in favor of this strategy is that the cumulative emissions approach provides very little information about the technical feasibility and cost implications of following a particular emissions pathway, and that it is this information that policymakers need to decide on future emission goals [*Rogelj et al*., 2011]. The quest for this information is understandable because it is the fossil-fuel emissions that need to be reduced; they continue increasing unabated and are the main perpetrator for disturbing the GHG balance of the atmosphere.

Still, addressing sustainability in the LUC sector must go beyond addressing what is occurring in the atmosphere alone (flow-based view). LUC scholars reasonably contend that a wider, more holistic systems view must be applied that also focuses on all parts of the terrestrial biosphere, irrespective of whether they are directly impacted by human activity (stock-based view), i.e., a view that encompasses both net LUC emissions and the residual land sink. The quest for sustainability means that these parts, as a whole, should achieve equilibrium (net carbon emissions zero balance) at long timescales, extending beyond the stabilization of fossil-fuel emissions. This sum over all stock changes is referred to as net biome production (NBP), which is zero at global equilibrium as is its net atmospheric flux [*Steffen et al*., 1998]. The rate and sign of carbon transport between stocks are, however, the result of dynamic processes determined by disturbances and perturbations driven by changes in climate as well as by LUC and management practices and methods. Currently, the NBP is positive, meaning that the terrestrial biosphere is acting as a global sink (residual land sink > net LUC emissions). There is high confidence that climate change will partially offset increases in the global land sink caused by rising atmospheric CO_2 (i.e., terrestrial ecosystems storing less carbon in a warmer climate), giving reason to conjecture that it can support transition to a low-carbon economy [*Ciais et al*., 2013].

Defining the state of sustainability of terrestrial ecosystems involves comparing their carbon stocks at two or more points in time, which is equivalent to following a cumulative (net) emissions approach. That is, the combined "terrestrial ecosystems-atmosphere" view of LUC experts requires conditions to be adhered to that are actually stricter than those applied to emissions from fossil-fuel combustion (atmosphere-only view).

As mentioned above, a systemic framework for tracking sustainability from a combined, environmental/ecological and socioeconomic (i.e., a socio-ecological) perspective needs to go beyond carbon and include biodiversity and other indicators that safeguard ecosystems and their functioning, including the combined cycling of C, N, and other elements. These indicators must allow for the setting of threshold and target values that reflect aggregated (stock-related) characteristics in addition to instantaneous (flow-related) system characteristics. Threshold and target values are keys to determining the benchmarks for the sustainability regime of the terrestrial biosphere (safe operating space), while the latter are relevant for determining operational and management options under a sustainable regime and for gaining a deeper understanding of what system changes are permissible.

Figures 1a and 1b and 1c and 1d, respectively, illustrate an expanded systems' view, which goes beyond an emissions-only system understanding toward a system that: (i) combines "terrestrial ecosystems" (Figures 1a and 1c in the lower panel) and "atmosphere" (Figures 1b and 1d in the upper panel), that is, stocks and flows; and (ii) integrates carbon and biodiversity as one (important) measure of impact. Although only a theoretical example, this systems exercise gives us a hint of the kind of modeling that we will need in the future. Figures 1a and 1b reflect a planetary environmental-boundary perspective that considers only climate-driven land-cover change. The simplified system studied is a tropical-like, biodiversity-rich LUC system with a moderate carbon stock (see black dot in Figure 1a), described by two parameters: terrestrial (soil and live biomass) carbon (C) and (plant) biodiversity (B). Changes in environmental conditions due to climate change are quantified by changes in global temperature (T) as proxy. Figure 1a illustrates the speculative case (without precluding alternative cases) that the LUC system, though poorer in terms of biodiversity, turns into a carbon sink in a warmer world. Here we presuppose that the C sink strength decreases with increasing environmental stress (T↑), and also that the LUC system as a whole flips from a C sink to a C source for a temperature increase greater than 4°C, e.g., due to increased C loss triggered by forest fires and drought induced tree mortality [*Allen et al*., 2010; *World Bank*, 2013]. Figure 1b shows the changes in carbon stock observed in the atmosphere as removals or emissions (see figure caption and Table S1, Supporting Information for additional information.)

Figures 1c and 1d build on Figures 1a and 1b. They reflect a combined planetary socio-ecological boundary perspective, here reduced to conventional land use not accompanied by conservation practices to meet global food demand, leading to a decrease in both C and B (brown dots in Figures 1c and 1d) related to land-cover change resulting from climate change (gray dots in Figures 1c and 1d). The decrease in C translates into decreased removals from and increased emissions to the atmosphere, respectively (see figure caption for additional information); while the combined effect in C and B leads to a decrease in the safe operating space to allow humanity to address global food security (as illustrated in Figure 2).

Figure 2 expands Figure 1 by taking a broader global as well as country perspective to delineate the scope for action. It indicates the safe operating space (green) with respect to agriculture, climate change (interpreted in terms of temperature as a single measure of impact), and food security (minimum quantity of food needed to sustain population). The area is determined by the maximum productivity of arable land while also taking into consideration alternative needs and uses of land (C storage, production of fiber and biofuels, etc.).

Although this is only an illustrative systems exercise, an important take-home message from Figures 1 and 2 is that they lead to conjecture that: (i) the LUC system can be described in terms of planetary boundaries, here C and B; and (ii) it is these two parameters—if they were to be met globally—that would need to be

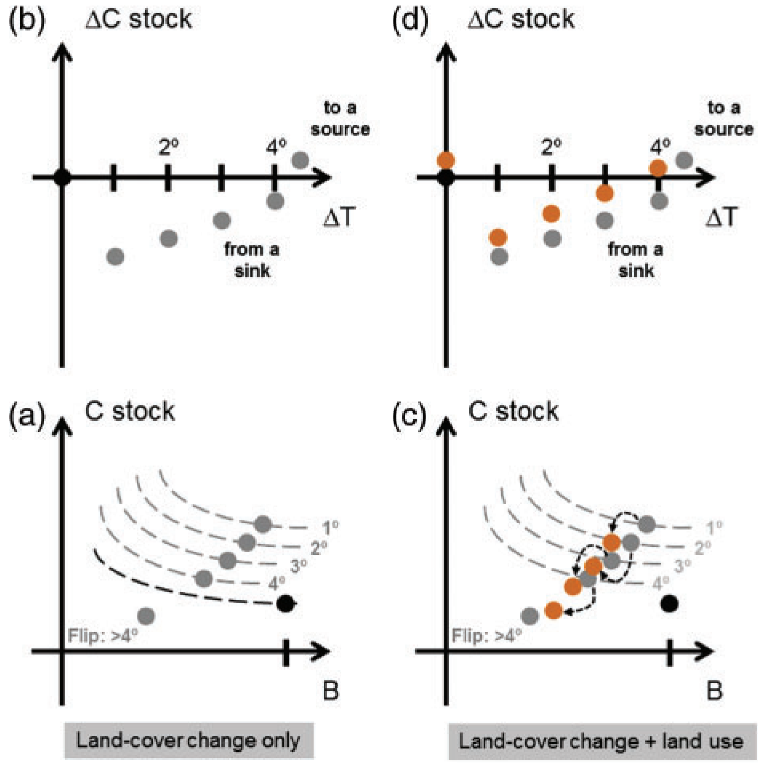

Figure 1. Combined terrestrial ecosystems-atmosphere view (lower versus upper figures) of a simplified LUC system. (a, b) Planetary environmental boundary perspective considering only climate-driven land-cover change. (c, d) Planetary socio-ecological boundary perspective considering land-use change, in addition to climate-driven land-cover change shown left (a, b), to meet global food demand. The simplified LUC system is considered to be a tropical-like, biodiversity-rich LUC system with a moderate carbon stock. It is described by two parameters: terrestrial (soil and live biomass) carbon (C) and (plant) biodiversity (B). The black dots in (a–d) mark the system's hypothetical initial state (stock versus flow equilibrium). Changes in environmental conditions due to climate change are quantified by changes in global temperature (T) as proxy. (a, b) Panel a illustrates the speculative (without precluding alternative cases) that the LUC system, though poorer in terms of biodiversity, turns into a carbon sink in a warmer world. The sink strength decreases with increasing environmental stress (T↑) and transmutes from a C sink to a C source for a temperature increase greater than 4°C. For the sake of simplification, the latitudinal dependence between C and B (approximated by a hyperbola) is maintained, while shifted, under higher temperatures. The change in carbon stock before (no climate change: black dot) and after (with climate change: any of the gray dots) is shown as "ΔC stock" in (b). ΔC stock is observed as removals or emissions in the atmosphere. Table S1 provides additional background information on (a, b). (c, d) Panels build on (a, b). They illustrate the case of conventional land use, not accompanied by conservation practices and thus leading to a decrease in both C and B (brown dots in c, d) related to land-cover change resulting from climate change (gray dots in c, d). The combined effect leads to a decrease of the "safe operating space" for humanity to address global food security (cf. Figure 2). The C feedback of land use on global temperature is not considered in (d) (the brown dots of c are entered in d at the same temperatures as the gray dots). As a result, the change in carbon stock before and after (ΔC stock) leads to decreased removals from and increased emissions to the atmosphere, respectively.

monitored and tracked across scales from local to global, given that the layers at which socio-ecological policies are implemented are nations, organizations, and individuals.

However, this is more easily said than done. Land-use activities causing changes in carbon stocks and flows, and other "ecosystem traits" occur locally and vary significantly from region to region. The impact of these local activities, however, accrues globally. Addressing this cross-scale cause-effect relationship, including the redistribution of ecosystem services between surplus and deficit regions [*Bindraban and Rabbinge*, 2011], is crucial for achieving sustainability globally. The systemic framework that we propose would be capable of achieving this. The framework would allow a two-track modeling approach to be followed, with the focus on the global scale as the first track and on the local-to-regional scale as the second. Each track would investigate sustainability from the socio-ecological perspective. The requirement to embed the local-to-regional scale, which comes with great detail and variability, within the global reference framework ensures that consistency is preserved across spatial scales (Figure 3). In essence, it is our use and management of natural resources—geographically specific by nature but accumulating far beyond local, eventually global, scales—that link ecosystem functioning with socioeconomic

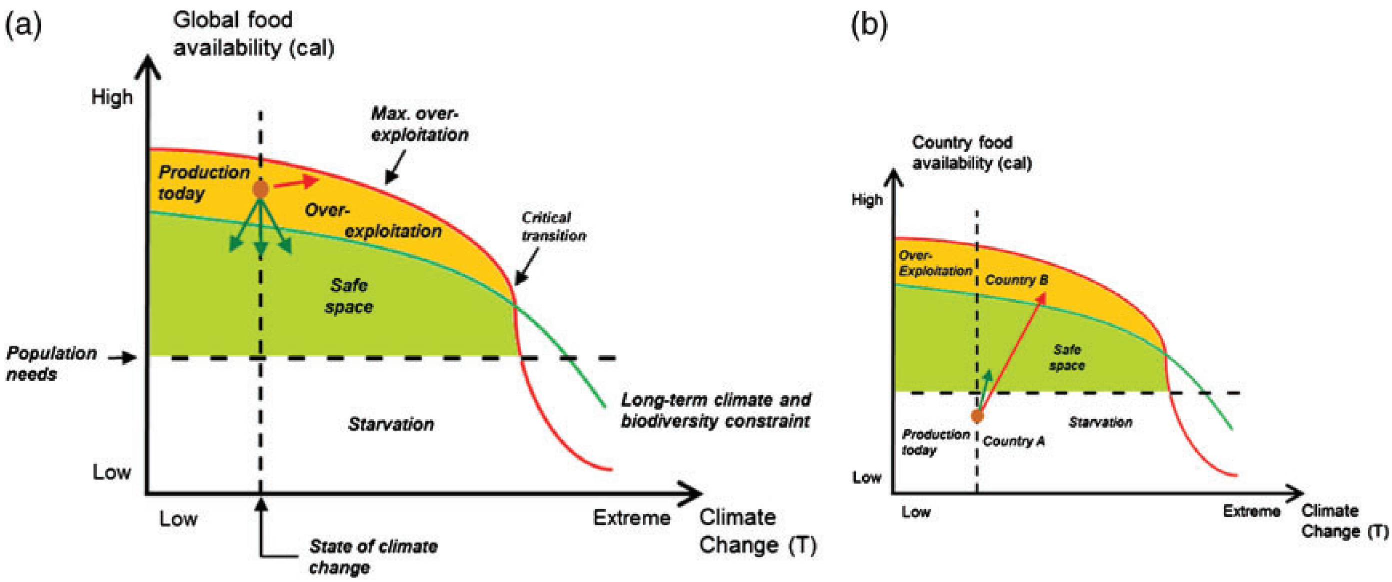

Figure 2. The planetary socio-ecological boundary perspective of Figures 1c and 1d expanded to delineate the scope for action. The figure indicates the safe operating space (green) with respect to agriculture, climate change (interpreted in terms of temperature as a single measure of impact), and food security (minimum quantity of food needed to sustain population). The area is determined by the maximum productivity of arable land also considering alternative needs and uses of land (C storage, production of fiber and biofuels, etc.). (a) Global food availability determined by planetary ecological boundaries. The brown dot reflects today's situation, which assumes that the world is already outside (above) the safe operating space as a result of overexploitation of depleting resources (fossil water, phosphorus, etc.), increased GHG emissions (from increased land conversion including deforestation, livestock production, etc.), and reduced ecosystem services (pollination, recreational value, water purification, etc.) due to biodiversity loss and ecosystem destruction. In further consequence, ecosystem resilience is reduced and the risk of critical transition (collapse of ecosystem services) arises. Red pointer: Present trend of food demand. As a result of no climate governance and conservation policies being in place, a classical "tragedy of the commons" situation arises. The current trend points to even higher overexploitation due to a growing population, increasing living standards, and changing dietary preferences toward higher meat consumption. Green pointers: Altered trends of food demand. These are anticipated to result from policies in place which favor nature conservation (C sequestration, B preservation, etc.), encourage and motivate sustainable dietary preferences, and minimize (or even counteract) negative feedback on climate. (b) Country food availability, here for a low-productive country (brown dot) whose arable area is under high demand and whose population depends on import (green and red pointers) to satisfy food needs (e.g., Sweden). Without a globally consistent framework in place (red versus green pointer), local-to-global policy guidance cannot be provided to ensure that countries with low-food production and high competitiveness on the global market do not contribute to overexploitation in high-productivity countries (like Brazil).

development. Under sustainable land-use conditions, management practices would lead to socioeconomic development that respects the boundaries of ecosystem functioning as far as resource use is concerned. Local or regional overexploitation of natural resources would occur when these thresholds are crossed (or when cumulative resource exploitation crosses planetary boundaries at the global scale). The global perspective captures key elements impacting local decisions such as climate change and variability, crop price development, and biodiversity loss. The local or regional perspective determines natural resource use and management, as well as human well-being, to name just a few. What remains to be tested is the level of detail needing to be resolved at local-to-regional scales in order to be instructive at the global scale. However, we anticipate that this can happen in steps, eventually leading to a well-structured bidirectional hierarchy: from local-to-global and from global-to-local.

Our two-track approach is motivated by: (i) the need to overcome the scale mismatch between achieving sustainability at the planetary scale and implementing accountable measures at the local-to-national scale where beneficiaries and policy actors are located; and (ii) a similar two-track (global-to-local and local-to-global) modeling approach created by biologists and ecologists to help improve forecasting and monitoring [*Barnorsky et al*., 2012]. "Simple" systems analysis types of models make it easier to understand the importance of feedbacks and critical systems behaviors across scales; while integrated, (potentially) complex global models are more effective for whole-system forecasts and for investigating identified feedbacks in their full complexity [*Rietkerk et al*., 2011].

We suggest that the two modeling tracks be used in parallel. We are still unaware of many of the intricate interrelations of key system parameters (biodiversity, C, N, P, water, etc.) and how their characteristics (feedbacks, thresholds, critical transitions, etc.) emerge at the planetary scale. However, we can continue researching sustainability at local scales where our expertise of governing sustainability in terms of its dependency on the socio-ecological setting is most advanced and where an actual system breakdown

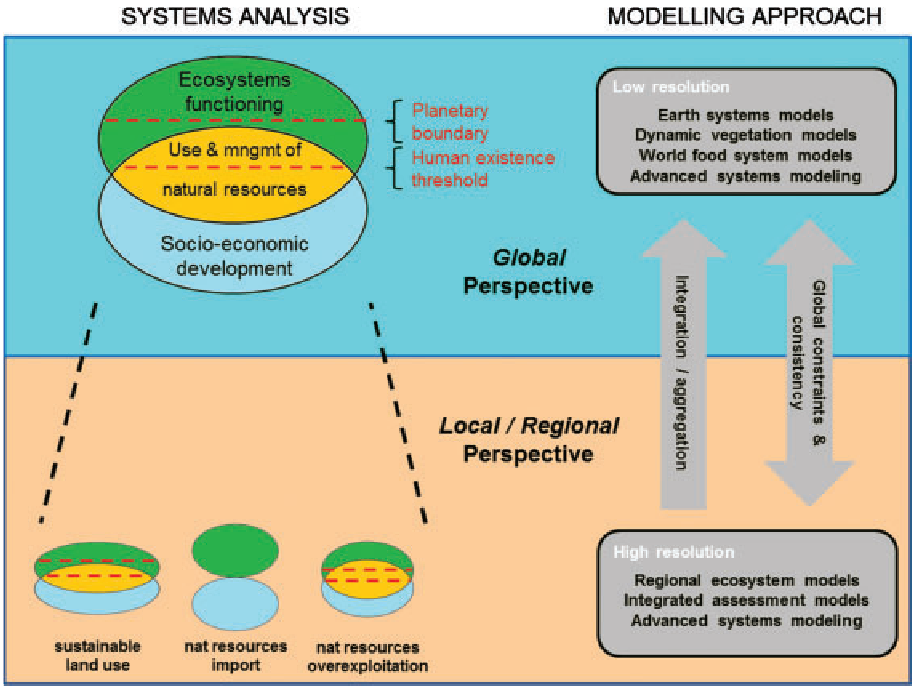

Figure 3. Systems analysis framework and modeling approach for human existence remaining within planetary environmental boundaries (LUC perspective; color coding similar to that in Figure 2). At the global level, sustainable land use must fall in-between planetary boundaries supporting ecosystem functioning and biotic requirement thresholds required for human existence (depending on defined lifestyles and distribution patterns). The local/regional framework perspective here illustrates two cases where use and management of natural resources deviate from a tolerable mode of using and managing natural resources sustainably: (i) the natural-resources-import (nat resource import) case—e.g., an arid country that depends on imported food for sustaining its population; and (ii) the natural-resources-overexploitation (nat resources overexploitation) case—e.g., a country that overexploits its natural resources beyond locally tolerable limits. The framework supports the integration across local/regional scales and the assessment of sustainability in the context of global environmental boundaries and socioeconomic constraints. To facilitate the contrast between global and local/regional, it is sufficient to perceive socioeconomic development in the figure as a whole, even though, in general, social development and economic development are resolved individually, as are their intersections (conjoint and with the environment, reflected in the figure by "ecosystems functioning").

might give rise to deeper insight into how to reach a sustainable state. We can adjust the planetary-scale sustainability framework independently in line with our increased insights at that scale and also by building on relevant insights gained locally.

Setting up a globally consistent and holistic framework is not difficult if we restrict our combined socio-ecological perception of sustainability to atmospheric GHG emissions. As many of the major GHGs remain in the atmosphere for tens to hundreds of years after release and are well mixed globally, the emissions-only perspective simply provides a framework that reflects average atmospheric conditions relevant to all spatial scales. However, if we broaden our perception of sustainability to embrace other system parameters and characteristics that are equally if not more relevant to the terrestrial biosphere system, the task immediately becomes more complex. The main problem is that our knowledge of how these system parameters and characteristics are spatially distributed is partial at best, as there are no sufficiently powerful measurements and monitoring activities available across the globe. Most of our knowledge is limited to local scales. Comparisons between local scales are confounded by large variations in systems' parameters and characteristics. Moreover, scaling up from these could confront us with a paradoxical situation: when system responses such as hysteresis in vegetation states are averaged over larger areas, we discover that characteristic signals are removed or considerably weakened [*Higgins and Scheiter*, 2012].

As a first step toward realizing the two-track approach described above, while leading us naturally on to the global-scale modeling track, we thus see the need for a "simplified" generic type of systems modeling that informs and supports not only the increasingly detailed socioeconomically driven policy response models, but also the ecologically driven dynamic vegetation models that already exist, or are being developed, so that the LUC can be synthesized at the global scale. These models would be detail-reduced without compromising the necessary system complexity, and they would be applied to study the multitude of environmental responses and interdependent constraints of the terrestrial biosphere. Similarly, the models would serve as a means of grasping uncertainty and anticipating critical thresholds and systemic surprises — the latter potentially being hidden in the interdependencies and dynamics of constraints, at scales for which data are available (typically, local to regional).

The models would provide crucial guidance in addressing the challenge of sustaining Earth's natural capital and ecosystem services in the future. They would play a similar role, e.g., to that of the energy balance models (EBMs) that were developed as the forerunners of the more complex general circulation models (GCMs). EBMs were a useful guide for developing GCMs, as they had to reproduce fundamental characteristics of the Earth system, e.g., the three equilibria of the Earth: two stable equilibria (ice-free and ice-covered Earth) and one unstable equilibrium (partially ice-covered Earth).

To make the step from global to national or finer scales, the detail-poorer global-scale modeling track would have to be exposed to the detail-richer socio-ecological expertise — available or still to be acquired — which relates to how sustainability is modeled and governed at local or national scales. Countries address sustainability and meet environmental boundaries differently depending on how those boundaries are embedded socio-ecologically. Here we examine the experiences of Brazil, an LUC hotspot, where land-use and land-cover issues play a key role not only domestically but also far beyond country borders. Above and beyond Brazil's position as an LUC player of global relevance, the case study also confirms what is to be expected: mentally, we appear to be better prepared to address the environmental/ecological dimension than the socioeconomic dimension of linking global and local — even though neither is understood. The mindset of the social science community is not yet aligned globally, and this would be a prerequisite for a scholarly debate on this issue [*van Langenhove*, 2012].

3. Case Study: What Can Be Learned Globally From Brazil's Domestic Efforts for Sustainability?

The ecological challenge for Brazil of achieving sustainable land use in an environmentally constrained world poses a multitude of social challenges. These include: (i) securing food production, both to meet increasing demands locally and to service the growing markets for export [Brazil already ranks among the top three export markets; *Accioli and Monteiro*, 2011], all while attaining environmental conservation and reducing pollution; and (ii) reducing poverty while improving nutrition as well as health and quality of life — a matter of major concern for Brazil's rapidly growing middle class [*Soares et al*., 2010; *Chappell et al*., 2013]. Brazil is also facing a dramatic change in its population-age structure. The total fertility rate has dropped to below replacement level (from 6.2 children per woman in 1950–1955 to 1.9 in 2005–2010), resulting in a rapidly aging population [*UN*, 2013]. The United Nations estimates that almost 20% of Brazil's population will be 65 years and older in 2050 [*UN*, 2002]. These changes, taken in conjunction with the consumption-age profile, indicate that the impact on emissions could be considerable and should be factored [*Lee*, 2011; *Lee and Mason*, 2011; *Zagheni*, 2011; *de Lima Amaral et al*., 2013]. Guidance that anticipates critical systems behavior at local/regional or national scales, subject to global-change processes of various kinds, can serve as an important complementary tool for informing national policymakers and stakeholders in their efforts to meet the challenges of sustainable development.

Brazil has been proactive and preeminent in tackling the mitigation of GHG emissions in: (i) the historical and successful PRODES program to estimate deforestation in the Brazilian Amazon (http://www.obt.inpe.br/prodes/index.php), followed by a comprehensive plan for prevention and control of deforestation [*PPCDAm*, 2013]; (ii) its credit program for low-carbon agriculture, which stimulates the large-scale expansion of sustainable practices such as no-tillage agriculture and integrated "crop-pasture-forestry" land use [*Plano ABC*, 2012]; and (iii) its growing willingness to discuss emission targets and improvement of agricultural productivity, while reducing the land area needed to achieve the same production. With reference to the simplified LUC system, which we discussed above from a combined terrestrial ecosystems-atmosphere and carbon-biodiversity perspective, it is important to highlight that monitoring of carbon emissions across all sectors and spatiotemporal scales is improving substantially in Brazil. However, equivalent monitoring is not conducted for biodiversity that is inferred only indirectly from changes in land cover.

Brazil is an important producer of agricultural commodities: one of the world's largest producers of beef, sugar cane, and sugar cane-derived ethanol, coffee, oranges, and soybeans (http://faostat.fao.org/). The country has one of the lowest net-carbon emission-per-energy production matrices globally [*Ometto et al*., 2013], and it is spearheading the development of both biomass-based fuels and hydroelectric power. Nearly 90% of the automobiles sold in Brazil in 2012 were flex-fuel cars, amounting to more than 50% of the total automobile fleet. Advances in processing sugar cane have allowed for energy self-sufficiency in ethanol production (energy produced from sugar cane bagasse, the dry dusty pulp that remains after the extraction of juice from the sugar cane, with unused energy being fed into the national grid), and increasing exportation of ethanol to other countries. The ambitious program of ethanol production in the past, which took Brazil by leaps and bounds to the achievement of energy independence, is being damaged by the efforts currently under way to extract oil from recently explored deep-water reserves. Despite the economic importance of these reserves, no national discussion is taking place about how to compensate for the future environmental effects resulting from their exploitation.

At the same time, Brazil's initiatives in agricultural production and its role as a global supplier of biomass products are drivers for LUC activities. Historically, the matrix of LUC in Brazil was shaped by a number of actions: (i) Portuguese colonization; (ii) the subsequent opening up by explorers of the interior of the South American continent; (iii) the establishment of the country's borders; and more recently (iv) governmental efforts to expand agricultural frontiers. Federal programs in Brazil in the 1970s contained large-scale credit and tax incentives to colonize frontier areas in the country [*Moran*, 1993]. This led to large migration flows to the northern part of the country and to deforestation and changes in the use of land. Lack of official land-title documents and a demand for agrarian reform also had impacts on the observed changes in land use [*Soares-Filho et al*., 2005]. The expansion of agro-businesses (soy bean, cattle, and timber production) combined with investments in infrastructure (roads, ports) led to significant changes in land use in several biomes, but most saliently in the Cerrado and Amazon regions [*Soares-Filho et al*., 2005; *Ludewigs et al*., 2009; *Lapola et al*., 2014]. A recent study suggests that an extensive and multilevel network of markets, information flow, and capital have been driving the recent LUC in the Amazon region, thus linking deforestation to a suite of stakeholders at regional and global levels [*Dalla-Nora et al*., 2014].

The resulting intricate links and trade-offs make Brazil a very worthwhile case study for our framework of analysis. The expansion of agricultural production in recent years has not happened at the expense of natural vegetation [*Lapola et al*., 2014]. Although according to a recent communication of the Ministry of Science, Technology and Innovation of Brazil (http://www.mcti.gov.br/index.php/content/view/347281.html), agricultural sector emissions have overtaken emissions from LUC including deforestation, the country's GHG emissions portfolio is still strongly associated with LUC. The country is acting at several levels to curb depletion of natural vegetation, including dense tropical rainforest, semiarid regions, and savanna. Deforestation rates were reduced between 2005 and 2012 by over 80% in the Amazon region and by 50% in other important biomes—these biomes include: (i) the Cerrado, a vast tropical savanna ecoregion accounting for 21% of Brazil's land area; and (ii) Caatinga, an ecoregion in northeast Brazil comprising nearly 1 million km^2 of xeric shrubland and thorn forest. However, the local and national institutional governance in the regions toward an integrative and sustainable framework for land use and social benefits is still weak [*Pinho et al*., 2014]. Federal legislation has imposed a series of restrictions and limitations to land change (as discussed below), but local governments still need to develop capacity; they face strong limitations culturally, and also in terms of weakly enforced laws and lack of skilled personnel [*Fatorelli and Mertens*, 2010; *Soares-Filho et al*., 2014], to name a few. The governance capacity in some states of the center-west and northern part of the country has shown signs of improvement in recent years. Nevertheless, the institutional frameworks at the national and local levels are disjointed, and are also constrained by the limitations mentioned above and by the lack of basic infrastructure [*Fatorelli and Mertens*, 2010]. An improved institutional framework would have positive impacts on the context of sustainable development [*Batistella and Moran*, 2005].

The Brazilian case study therefore shows that it would be incorrect to assume that there is anything like direct compliance with legislative initiatives. An important lesson learned from successful reduction in deforestation is the importance of providing intense and frequent monitoring, making data available to the broader public, and controlling illegal forest clearance activities.

Growing domestic and global demand for agricultural commodities, together with regional development projects, have been increasing pressure on land in Brazil. The outcomes of legislation relating to the Brazilian Forest Code, an important environmental law passed in 1965, can be highlighted as a critical example of this. The Code requires landowners to preserve part of their property as natural reserve (the conserved area depends on the region in which the property is located). The Code has been heavily contested by landowners and political representatives alike, while increasing demand for biomass products and rural development initiatives have been feeding the controversial debate still further.

In 2012, Brazil's Senate and National Congress approved the new Forest Code. The amendments to the Code: (i) define how land is "occupied" and what portion of this land can be changed from its natural vegetation cover; (ii) reformulate some of the existing principles and concepts of land use in Brazil, and rank land cover to property area, thus changing the amount of native vegetation conserved at the regional level; and (iii) support, under specific conditions, an amnesty for deforestation actions that occurred prior to mid-2008. Perhaps the most important achievement of this new law is the Rural Environmental Cadastral System, which requires all properties to be geo-referenced, thus allowing better control over land-use and land-cover changes [*Soares-Filho et al*., 2014].

This development also explains why production of, and trade in, biomass are particularly relevant to Brazil's emissions balance. Brazil exports much of its agricultural commodities, and no trade-embodied emissions are accounted for. This system, which needs to change, underscores the need to find sustainable, low-carbon means of improving yield and expanding agriculture in ways that not only enhance services provided by ecosystems and biodiversity, but also add value to them. The controversy over Brazil's Forest Code illustrates the mutual links between socioeconomic development and ecosystems functioning via resource management and, very specifically in this case, land-use practices. Brazil's relatively low level of fossil energy use and associated GHG emissions comes at the cost of increased pressure on the biologically productive land area available. This is a trade-off with very strong implications for the road map toward sustainable land use, once socioeconomic boundaries are more strongly emphasized at the regional level.

There are major challenges to be faced at local levels. In the Amazon, e.g., efforts to increase both human well-being and ecosystem services have proved to be short-lived at the deforestation frontier and in LUC-affected regions [*Pinho et al*., 2014]. Initial improvements soon fell off. An analysis of multiple municipalities in the Amazon suggests that improvements to living standards, literacy, and life expectancy occur when deforestation begins, but decline as the frontier advances [*Rodrigues et al*., 2009]. Proximity to markets and life cycles also have significant effects on the choice of land-use system, but in a nonlinear fashion: landowners adjust their land-use systems based on market stimulus but are constrained by the viability of the soil type. The more time smallholders spend on the frontier, the greater their ability to process exogenous sources of information, such as price changes in national and international markets, and thus the more efficient the choices they make with respect to labor-related and biophysical constraints [*VanWey et al*., 2012]. That is, agricultural productivity is not only a function of soil and climate but depends also on learning, indicating an important socioeconomic element to be considered in our framework. However, these patterns may change in the near future with the occurrence of urbanization processes. Historically, regional environmental policies have not focused on improving the well-being of rural populations [*Wunder*, 2006; *Pinho et al*., 2014]. At the deforestation frontier, enforcement of environmental legislation has been uneven, detracting from what has otherwise been a success story. The incorrect perception that there is an unending supply of forested land, which can be transformed, overlooks the important role of forests in stabilizing climate globally and offsetting intensive agricultural and urban-industrial development in other parts of the country. Part of the problem is clearly a lack of connection between local/regional, national, and global targets—which the systems-analytical framework that we propose would allow tackling.

Similar experience exists for other regions of Brazil. Expansion of agriculture in the Cerrado has brought local economic success stories. However, it is not clear how the improved economic standard is distributed across society. In some areas, considerable parts of the population face poverty and low-education levels. In other areas, where agriculture has expanded widely, there has been a depletion of environmental services and biodiversity. Thus, any research framework envisioned with respect to aggregation of local/regional or national sustainability practices at the global scale needs to consider (measure) the transfers of resources, opportunities, and life improvements across the various segments of society, within and across countries.

Scientific knowledge gained at local scales in Brazil (and tropical countries in general) does not always permeate through society and the decision-making process. Learning from research that highlights the strong interdependence between sustainability and human well-being [*Rogers et al*., 2012] could transform the current development model applied in the tropics, even while ensuring respect for planetary boundaries [*Rockström et al*., 2009]. Moreover, human well-being needs to be conceptualized in ways that go far beyond simple economic measures such as gross domestic product [*Kahnemann and Krueger*, 2006; *Stevenson and Wolfers*, 2008; *Fleurbaey*, 2009]. They need to take into account the effects of globalization and, locally, the role of culture and social understanding of the environment. It is this advanced perception of well-being that needs to be injected into a research framework, e.g., the goal functions of social sustainability models, and translated from the local to the global scale.

A growing body of scholarship suggests that reducing economic inequality in any cultural system is key to broad-based improvements in human well-being and environmental sustainability [*Eckersley*, 2006; *Wilkinson and Pickett*, 2009; *Rogers et al*., 2012]. In the past 20 years, having a more stable economy has allowed Brazil to implement some of the largest-scale projects in the world for the financial support of poor families. These aim to reduce poverty in the short term and increase human capital in the longer term through better youth education [*Soares et al*., 2010]. There is a strong argument that the social and economic changes required to ensure transition toward sustainability depend on centralized efforts to reduce economic inequality. Policy priorities need to be changed so that material consumption is reduced, human relationships become more rewarding [*Moran*, 2006, 2010], and economies become more resource-efficient [*EC*, 2011]. These are "bottom-up" insights. However, they need to be generalized and applied more widely so that they are reflected at larger spatial, eventually global, scales.

Climate change effects on agricultural production have the potential to impact population mobility [*Barbieri et al*., 2010]. It is argued that the populations most vulnerable to climate impacts will move to other areas, including forest frontiers or urban areas. The latter frequently lack basic infrastructure to cope with strong migration over short time periods [*Barbieri et al*., 2010; *Feng et al*., 2010; *Black et al*., 2011]. Thus, future efforts to support transition toward sustainable LUC also need to tackle and integrate challenging and innovative areas of research that target the full range of causes, climate-driven and beyond, and solutions: technical, cultural, and political. There are enormous cultural variations in consumption patterns, attitudes toward the natural environment, and economic development. Policymakers must take these into account if they are to achieve local-to-globally consistent emission and other environmental goals.

In any evaluation of policy-relevant actions, the interaction between intraregional factors within a country should be considered. These include infrastructure projects, protected areas, law enforcement, and external forces such as increases in local and global demands for food and biofuels. Mechanisms that valuate the natural environment, its biodiversity, and ecosystem services are based on aggregated indicators that are used by local and national policymakers and stakeholders. Thus, putting mechanisms such as Payment for Ecosystem Services (PES), Investment on Natural Capital (PINC-GCP), and Reducing Emissions from Deforestation and Forest Degradation (REDD+) on the policy agenda and promoting them is important for Brazil and, indeed, for the entire tropical belt. However, these and other mechanisms need to work in an integrated manner—which could be substantially buttressed by a systems-analytical framework in place. Investments need to go hand-in-hand with socio-ecological sustainability principles. Otherwise, they are likely to fail.

4. Conclusion

Using Brazil as a case study is enlightening, as it provides two important lessons as follows:

1. Brazil is an LUC player of global relevance. Whether or not—or, indeed, how—it takes action, is felt far beyond its own national territory. This is already apparent at the planetary scale in terms of GHG emissions and other environmental criteria, and it is becoming increasingly evident as environmental constraints grow.

2. As Brazilian policymakers struggle to meet the many dimensions and socio-ecological challenges of sustainability arising within their own national boundaries, they cannot be expected to have any realistic understanding of the global implications of the national measures that they are taking. This is because no appropriate "guidance" or "roadmap" for local-to-global sustainability policies yet exists, either in Brazil or elsewhere.

A framework is thus needed that can systemically guide and facilitate decision making on sustainability—in Brazil and all countries—from the planetary to the local level, and vice versa. Such a framework would be globally consistent and expandable to allow the incorporation of new knowledge, e.g., local/regional or national expertise and best practices.

This requires the elaboration of a modus operandi which ensures:

1. effective learning from locally gained insights where expertise of governing sustainability from a multiscale socio-ecological perspective is most advanced; and
2. reflection of those insights across and at larger scales.

To establish such a framework, we argue that a two-tier modeling approach, based on a systemic framework, should be designed that allows sustainability to be addressed from a socio-ecological perspective. The first tier would focus on the global scale and the second on the local-to-regional scale. Both would be supported by additional modeling strands to help trace the coupling and cascading of feedbacks and critical systems behaviors across scales, from local-to-global, and vice versa.

Advancing our Earth systems understanding from the top down is cumbersome. A growing number of regional and subregional climate and environmental initiatives are being adopted in the absence of effective global collaboration. Such initiatives are vital. However, as suggested here, they need to be "pulled together" within a systems framework and supported by carefully designed data-monitoring schemes in order to optimize the efforts already under way and those planned for the coming years.

It is our belief that, based on the experience of Brazil, the development and implementation of such a systems framework for sustainability decision making will not only fill current gaps in sustainability knowledge, but go a long way toward helping societies stay within the safe operating space for humanity represented and delineated by the planetary boundaries.

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