Copyright © 2013 by the author(s). Published here under license by the Resilience Alliance.
Robèrt, K.-H., G. I. Broman, and G. Basile. 2013. Analyzing the concept of planetary boundaries from a strategic sustainability perspective: how does humanity avoid tipping the planet? *Ecology and Society* **18**(2): 5. http://dx.doi.org/10.5751/ES-05336-180205

Insight

Analyzing the Concept of Planetary Boundaries from a Strategic Sustainability Perspective: How Does Humanity Avoid Tipping the Planet?

Karl-Henrik Robèrt [1,2], *Göran I. Broman* [1] *and George Basile* [3]

ABSTRACT. Recently, an approach for global sustainability, the planetary-boundary approach (PBA), has been proposed, which combines the concept of tipping points with global-scale sustainability indicators. The PBA could represent a significant step forward in monitoring and managing known and suspected global sustainability criteria. However, as the authors of the PBA describe, the approach faces numerous and fundamental challenges that must be addressed, including successful identification of key global sustainability metrics and their tipping points, as well as the coordination of systemic individual and institutional actions that are required to address the sustainability challenges highlighted. We apply a previously published framework for systematic and strategic development toward a robust basic definition of sustainability, i.e., the framework for strategic sustainable development (FSSD), to improve and inform the PBA. The FSSD includes basic principles for sustainability, and logical guidelines for how to approach their fulfillment. It is aimed at preventing unsustainable behavior at both the micro, e.g., individual firm, and macro, i.e., global, levels, even when specific global sustainability symptoms and metrics are not yet well understood or even known. Whereas the PBA seeks to estimate how far the biosphere can be driven away from a "normal" or "natural" state before tipping points are reached, because of ongoing violations of basic sustainability principles, the FSSD allows for individual planners to move systematically toward sustainability before all impacts from not doing so, or their respective tipping points, are known. Critical weaknesses in the PBA can, thus, be overcome by a combined approach, significantly increasing both the applicability and efficacy of the PBA, as well as informing strategies developed in line with the FSSD, e.g., by providing a "global warning system" to help prioritize strategic actions highlighted by the FSSD. Thus, although ongoing monitoring of known and suspected global sustainability metrics and their possible tipping points is a critical part of the evolving sustainability landscape, effective and timely utilization of planetary-boundary information on multiple scales requires coupling to a strategic approach that makes the underlying sustainability principles explicit and includes strategic guidelines to approach them. Outside of such a rigorous and systems-based context, the PBA, even given its global scale, risks leading individual organizations or planners to (i) focus on "shares" of, e.g., pollution within the PBs and negotiations to get as high proportion of such as possible, and/or (ii) awaiting data on PBs when such do not yet exist before they act, and/or (iii) find it difficult to manage uncertainties of the data once such have arrived. If global sustainability problems are to be solved, it is important that each actor recognizes the benefits, not the least self-benefits, of designing and executing strategies toward a principled and scientifically robust definition of sustainability. This claim is not only based on theoretical reasoning. A growing number of sectors, businesses, and municipalities/cities around the world are already doing it, i.e., not estimating "allowed" shares of, say fossil CO_2 emissions, but gradually moving away from unsustainable use of fossil fuels and other unsustainable practices altogether.

Key Words: *framework for strategic sustainable development; planetary boundaries; planning; strategy; sustainability; tipping points*

INTRODUCTION

A fundamental need for moving toward global sustainability is to develop robust and effective means to address the growing number of sustainability challenges being faced. The need is compounded by the fact that sustainability challenges are typically "discovered" rather than predicted in any consistent and robust way. Rockström et al. (2009) proposed a new approach to understanding global ecological sustainability based on defining planetary boundaries (PBs) within which humanity must remain to operate safely. We will call this approach the planetary boundary approach or PBA. Nine PBs are initially proposed, along with quantitative metrics for seven of them. "The proposed concept of 'planetary boundaries' lays the groundwork for shifting the approach to governance and management of sustainability challenges away from the essentially sectoral analyses of limits to growth aimed at minimizing 'negative externalities,' toward the estimation of the 'safe space for human development'" (Rockström et al. 2009). However, the authors also describe the challenges in fully elucidating a complete set of PBs and indicators, including inherent uncertainties in defining and predicting PBs and associated indicators, as well as the need to link together strategic actions toward sustainability from the individual to the institutional and global levels. Thus, the PBA, as an integrated framework aimed at identifying a safe global operating space for human development, must be connected

[1]Blekinge Institute of Technology, [2]The Natural Step, [3]Arizona State University

to other sustainable development efforts that support strategic actions on the ground, and can address uncertainties inherent in PB-scale metrics and quantitative descriptions.

Given the opportunity presented by the PBA as well as the inherent challenges, a critical question is then: what is a robust and effective way to provide strategic leadership and innovation within the emerging context highlighted by an evolving global “sustainability dashboard” such as planetary boundaries?

We propose that to have an effective and truly strategic approach to sustainable development, the ongoing estimation of the PBA’s “safe space for human development” must be coupled with decision making that employs basic sustainability principles (SPs) and proactive strategic guidelines, including a logical and practical methodology for moving toward fulfillment of these principles. Such an approach has been developed: a framework for strategic sustainable development (FSSD) that applies basic principles for sustainability and includes a planning mechanism for their application. The application of the FSSD addresses at least three fundamental challenges within the PBA:

1. The current PBA does not integrate the underlying mechanisms for deviations moving us toward even known critical PBs. Clarity about such mechanisms is important for early corrective actions or for avoidance of problems even before they arise, as well as for avoiding solving one problem and creating another, i.e., to design problems out of the system. A complete set of such mechanisms, formulated as principles for sustainability, can provide an integrated systems approach to sustainability strategies. A simple analogy would be: a basic principle for avoiding obesity is that food energy uptake must not be systematically greater than energy expenditure. The “boundary” perspective would focus on studying how obese one can become before the risk for succumbing to obesity becomes substantial, i.e., before one reaches a tipping point. There is nothing in such a boundary approach, in this case studying dangerous levels of obesity, that excludes being clear about the basic mechanism for becoming obese. Being clear about that basic mechanism allows for not only more strategic reactive actions, but also proactive and preventive actions so to not run into obesity dangers at all.

2. PBs contain inherent uncertainties, including the challenge of knowing when all critical boundaries have been identified. A proactive and preventative approach that can work pragmatically given the embedded uncertainty is required. Because the FSSD presents such a strategic planning and decision making model, it does not require exact knowledge of PBs or detailed knowledge on tipping points to create robust, systems-based action strategies.

3. On the condition that the underlying basic mechanisms are known, as outlined in (1) above, losing the organizational or sectoral dimensions might in fact slow down proactive ongoing change toward sustainability because many of today’s organizational and sector actors directly link individual decision making and institutional impacts with sustainability challenges at the global scale (Ostrom 2009, 2012). Doing so, they can also make the lives of proactive policy makers easier by providing them with support via reinforced feedback loops. Yet, we too recognize the current limitations of today’s approaches with only a firm or sector-scale focus, e.g., because the pace of change of society at large may be too slow if it is to rely solely on ripple effects from proactive role models. Thus, it is critical that a strategic approach provides both guidance and incentive for cooperation across value chains/networks in business, regions, and nations. To increase the utility and efficacy of the PBA, it seems critical to combine its boundary metrics with explicit expressions of the underlying mechanisms that drive the system toward these boundaries. Together with strategic guidelines for planning and decision making that do not contribute to those mechanisms, it would then be possible to work strategically toward sustainability at multiple scales and across multiple disciplines and sectors. The FSSD provides such a vehicle to link individual decisions to the global sustainability challenges highlighted by the PBA.

In sum, the gradual decline of the biosphere’s potential to sustain civilization in the face of growing global societal needs, as outlined in the PBA as well as the FSSD, can be metaphorically described as a funnel. As long as societal structures do not prevent unsustainable system behavior, increasing pollution and decreasing economic accessibility of natural resources will represent the walls of a funnel and function as systematically harsher constraints on human activities. Individual actors that rely on unsustainable practices are exposed to a systematically higher relative risk of economically hitting these funnel walls. This translates into higher costs for resources, waste management, insurance, taxes, bad publicity, and as higher opportunity costs for the timely development of sustainable practices to meet human needs further ahead in the funnel (Holmberg and Robèrt 2000). The exploration of the PBA and FSSD together provides novel insights into how to more effectively address this narrowing funnel.

FRAMEWORK FOR STRATEGIC SUSTAINABLE DEVELOPMENT (FSSD): AN OVERVIEW

To be strategic, from the very start one should distinguish the definition of the objective of the planning from the process by which the objective is approached in the system within which one is acting. Military (for example, Clausewitz 1832) and civilian (for example, Mintzberg et al. 1998) strategic planners have long known this. The FSSD recognizes this and is comprised of five specific levels (Robèrt 2000).

The system level (1) describes the overall major functions of the system, in this case the biosphere with its human society, our knowledge on stocks, flows, biogeochemical cycles, biodiversity and resilience, and the basic relationships between human practices and their impacts. The current systematic degradation of this system is the rational for the levels that follow. To apply an analogy, in chess, the system level contains the rules of the game.

The purpose level (2) specifies the definition of the objective, in this case, success within sustainability. Returning to the analogy, to checkmate one's opponent is the purpose, which can happen in almost uncountable combinations all complying with the same basic principles of checkmate. The next level requires this key second level.

The strategic guidelines level (3) specifies the guidelines for how to approach the objective strategically. This implies a step-by-step approach toward the objective in a way that ensures that financial, social, and ecological resources continue to feed the process. In chess, moves serve as strategic steps to checkmate. Trade-offs are selected from their capacity to serve as platforms toward complying with principles of success (level 2), rather than as choices between inherent evils.

The actions level (4) comprises everything done in concrete terms, e.g., in chess, the actual moves. Here, strategic guidelines at level 3 are applied to inspire, inform, and scrutinize every action or investment that is put into a strategic plan.

The tools level (5) includes the concepts, methods, and tools that are often required for decision support, monitoring, and disclosures of the actions (4) to ensure they are chosen strategically (3) to arrive stepwise at the objective (2) in the system (1). Examples in sustainable development are modeling, management systems, indicators, life cycle assessments, etc. In chess, this would include everything from books on how to play, to management systems to store and analyze game-by-game moves and outcomes.

It is the rigor by which levels (1) to (3) are described, thereby providing a robust basis for the planning and decision making, and allowed to inform each other, thereby providing mechanisms for internal and external consistency and integrity, which determines how confident participants can be when choosing appropriate actions (4) and appropriate concepts, methods, and tools (5; Robèrt 2000, Robèrt et al. 2002).

In many planning processes, level (2) is often either too detailed, e.g., when relatively detailed and static scenarios are used for backcasting in highly changing situations, or not fleshed out sufficiently in operational terms, e.g., when only the Brundtland definition (World Commission on Environment and Development 1987) is used. To be functional, the set of principles must be necessary to reach the objective, i.e., sustainability plus anything else that a team of planners agrees to add as mandatory. However, the set of principles should not be more than necessary, to avoid unnecessary restrictions and to reduce distraction. The set of principles must also be sufficient to cover all aspects of the objective. In addition, the set of principles must be general, to make sense for all stakeholders and thus allow for cooperation, concrete, to guide problem solving and actions, and distinct, to enable comprehension and facilitate development of indicators for monitoring (Ny et al. 2006, Robèrt et al. 2012).

Using the general requirements for principles for success, the following principles were derived specifically for sustainability:
In a sustainable society, nature is not subject to systematically increasing:

1. concentrations of substances extracted from the Earth's crust, such as fossil carbon or metals;
2. concentrations of substances produced by society, such as nitrogen compounds, CFCs, and endocrine disrupters;
3. degradation by physical means, such as large scale clear-cutting of forests and over-fishing; and, in such a society,
4. people are not subject to conditions that systematically undermine their capacity to meet their needs, e.g., from the abuse of political and economic power leading to decreasing interpersonal trust and decreasing trust between individuals and societal institutions.

The four principles were derived by asking the following question: by what primary mechanisms, upstream at the level of first approximation in chains of causality, do human activities set off downstream social and ecological impacts that will destroy this system? The answer revealed how a myriad of downstream impacts are rooted in a few upstream errors of societal design and operation. Thereafter, a "not" was inserted for each primary mechanism of destruction to form the above first-order sustainability principles, designed as exclusion criteria for redesign (for references, see Ny et al. 2006). The sustainability principles do not themselves state the many specific ways by which they can be violated, nor do they themselves provide means for quantitatively determining exactly when they are violated. For example, the first two principles do not say when emissions are larger than the assimilation capacity of the recipient, nor does the third principle say by what specific practices land can be degraded more and more. The sustainability principles help people in companies, municipalities, etc., to ask relevant questions and to identify how they contribute to unsustainability. The sustainability principles can also guide research, e.g., on indicators even before critical boundaries are trespassed. Returning to the analogy of obesity, it may be difficult to know exactly when the food energy uptake is larger than the energy expenditure, and the “obesity principle” does in itself not say anything about this nor does it in itself provide any means for measuring it, but that is not an argument for disregarding the principle.

The FSSD uses an application procedure with four general steps. In the first step (A), participants, selected by various methods, share and discuss the topic or planning endeavor, and agree on a principle vision of success framed by the sustainability principles (SPs) in level 2 of the FSSD. In the second step (B), participants explore the current situation. They list the main current challenges in relation to any vision they want to reach, informed by the SPs applied as boundary conditions, as well as current assets to deal with those challenges. Thereafter, participants turn to brainstorming (C), whereby they suggest possible future solutions to the challenges and scrutinize them only with respect to the vision within the SPs, temporarily disregarding constraints related to the current situation, e.g., constraints related to the current infrastructure, the current energy system, the current financial capacity, etc. Just because something is not affordable right away, e.g., changing to solely sustainable energy sources, does not mean that it cannot be part of a vision for a step-wise approach. In the final step (D), the strategic dimension comes to the fore when participants prioritize solutions, e.g., investment decisions or tool development from the previous step.

In this final step, priorities are set with an intuitive logic. This means a stepwise approach that ensures that early steps are designed to serve as (1) flexible platforms for forthcoming steps that, taken together, are likely to bring society, the organization, and the planning endeavor to the defined success framed by the SPs, by striking a good balance between (2) direction and advancement speed with respect to the defined success, and (3) return on investment to sustain the transition process. If these strategic guidelines are not combined, actors might, e.g., run out of money or other resources and find their competitive position diminished (Esty and Porter 1998), or pick measures that appear to be “low hanging fruit” but that may actually prove to be suboptimized or lead to dead ends (Broman et al. 2000, Holmberg and Robèrt 2000). The intuitive logic creates the opportunity for pragmatic leadership, not only looking at the promise of an improved bottom-line in the future, but also considering short-term profits designed in a way that opens up the potential for longer term profits. Lack of creativity and competence may provide a stumbling block and prevent essential technical changes over time, whereas an understanding of the inevitability of unsustainably driven changes in market conditions, as per the funnel metaphor above, is likely to reward those with the creativity and competence in strategic sustainable development. The FSSD allows for a self-benefit of sustainability proactivity to be captured by companies, regardless if other companies do it or not. In other words, strategic sustainability thinking can serve as a driver for companies to reduce their planetary impact as they strive to be competitive. What others do may influence the speed by which such progress is possible, whereas the overall direction toward sustainability is the same and guided by the FSSD (Ny et al. 2006).

RELATION TO OTHER METHODS, TOOLS, AND CONCEPTS FOR SUSTAINABLE DEVELOPMENT

The FSSD has been applied to assess the strengths and weaknesses of several methods, tools, and concepts. Examples are Ecological Footprinting (Holmberg et al. 1999, Robèrt et al. 2002), Factor 4 (Robèrt et al. 2000), Daly’s principles (Robèrt et al. 1997), ISO 14001 (Robèrt 2000, Robèrt et al. 2002, MacDonald 2005), LCA (Andersson et al. 1998, Ny et al. 2006), Industrial Ecology (Korhonen 2004), and Product Development Methods (Byggeth et al. 2007). The FSSD has been applied to assess existing products and industrial plants (Matsushita 2002, Ny et al. 2008). It has provided a basis for discussions to integrate concepts such as Zero Emissions, Cleaner Production, Sustainable Technology and Natural Capitalism (Robèrt et al. 2002), and Corporate Social Responsibility (Waage et al. 2005).

These studies conclude that there are many good methods, tools, and concepts for sustainable development. Each has its perspective, merits, and gaps. However, a well-structured, unifying framework has been missing, something to explain how the methods, tools, and concepts relate to sustainability and to each other. Together with pioneers of some of the most cited tools and concepts for sustainable development, we have shown how the FSSD increases the utility of individual methods, tools, and concepts by highlighting strengths and weaknesses, and enabling combinations that create more robust strategic approaches (Robèrt et al. 1997, 2000, 2002, Holmberg et al. 1999, Robèrt 2000).

EXAMPLES OF APPLICATIONS OF THE FSSD

As a guiding framework for strategic sustainable development, the FSSD has been applied in a number of contexts, including business, community, and policy. The FSSD has been applied in areas directly relevant to the proposed PBs. At Electrolux, a global manufacturer of household appliances, the FSSD was applied to not only move away from using ozone-depleting CFCs (chlorofluorocarbon), but also to move away from using any persistent cooling compounds foreign to nature. To phase out such compounds from consumer goods is an example of applying the second SP directly and without needing detailed numeric analyses. Introducing HCFCs (hydrochlorofluorocarbon), the standard approach at the time, would have meant an improvement in relation to CFCs with regard to ozone layer destruction potential. However, HCFCs, just like CFCs, are relatively nondegradable in nature, and therefore also problematic and expensive to safeguard within the constraints of SP 2. Also, future additional investments in a technology shift from HCFCs to HCs (hydrocarbon), a sustainable solution considering the amounts necessary and type of use, were estimated to be very high. Taken together, this meant that via the application of the FSSD, even though less damaging than CFCs and although an exact limit for their "safe" atmospheric concentration was not known, HCFCs were not seen as a solution but as a dead end. On the other hand, moving directly to HCs was deemed too risky at the time. HCs are explosive and the available refrigeration technology was not considered sufficiently ready to handle these cooling compounds in a safe way. Applying the FSSD, Electrolux designed a strategy building on an intermediate step of a cooling compound called R134a. This is a chlorine-free compound without deleterious effects to the ozone layer. However, this compound also does degrade slowly, and consequently comes with a high risk of increasing in concentration in natural systems with large-scale use, and it is a greenhouse gas. By applying the FSSD, Electrolux knew this was not a permanent solution. However, because it solved the acute problems related to the ozone layer, changing customer preferences, and probable upcoming legislation, and because future additional investments necessary to shift from this platform to an HC-based cooling technology was much more reasonable, this became a viable stepping stone. Electrolux introduced R134a into the production lines in a way that prepared the way for the next generation of refrigerators (HC-based), which have now been available for several years. Similar preemptive actions have been taken by Electrolux with regards to more sustainable metals management and energy strategies based on a new set of indicators informed by the FSSD (Azar et al. 1996). In October 2006, Leif Johansson, former CEO of Electrolux, declared in a public speech: "It was not until 10 years later that we fully realized how much money we had saved and earned from applying the FSSD to our business," thus highlighting the need for a long-term perspective and for strategic thinking.

In a community context, the Canadian municipality of Whistler's efforts at developing a strategic sustainability plan is an example of applying the FSSD (Gordon 2004). One exemplary project included negotiations with a local utility company. In this case, a proposal to build a pipeline for natural gas sized for energy use projections for the next 50 years and for supplying the 2010 Winter Olympics, based on the rational that natural gas has less carbon per energy unit than propane, was turned down. The backcasting questions related to the final step (D) of the FSSD led to the conclusion that the proposed $50-million investment could not be justified. The FSSD application led to a smaller natural gas pipeline, exploiting the short-term gains from the shift to natural gas, while freeing up money to follow a path to a sustainable energy system featuring a locally owned utility with geothermal, district heating, and other energy solutions with a higher sustainability potential, including creating 100 % renewable energy for Whistler's 2010 Winter Olympic effort (VANOC 2010). In the Whistler case, the FSSD also proved its strengths when it came to bringing together many different stakeholders, such as the business association, environmental groups, political parties, etc., to reach a consensus on a shared principled vision. Initially, these stakeholders had highly conflicting opinions about the development of the municipality.

In both of these examples, the application of the FSSD provided strong linkage and strategic guidance between long-term and large-scale sustainability issues with near-term and local-scale decision drivers. It enabled strategic action in the face of future uncertainty. In the case of Electrolux, a new suite of products was developed that decreased a variety of PB aspects, including climate and carbon emissions, water sustainability, and ozone protection, and secondarily addressed issues such as ocean acidification and land use (Basile et al. 2011). Whistler, in turn, also made long-term commitments to decreasing their carbon impact through renewable energy, as well as developing an integrated plan linking social needs to environmental sustainability (Whistler Municipality 2007).

GENERAL INTEGRATION OF THE PBA WITH THE FSSD

First, it follows from the description above that while the PBA seeks to define a core set of key boundaries at the planetary level and to estimate critical tipping points regarding associated variables, the FSSD offers basic sustainability principles and strategic guidelines that provide guidance for redesign toward sustainability. The complementarities create the opportunity for an integrated approach. The FSSD provides an overview of challenges, opportunities, and feasible transition routes toward sustainability, including challenges for practices where there are not yet any PBs determined. Knowledge about current values of PB variables and current rates of change can be used to estimate how much longer SPs can be violated and thereby provide an urgency basis and a defined set of variables for strategic prioritization.

Second, as Rockström et al. (2009) propose, the PBA does not automatically lead individual sectors or organizations to change or action. For most actors, change at a global level seems simply beyond their scale. However, the SPs of the FSSD are in fact formulated to offer exactly what Rockström et al. want, namely individual actors and sectors that have the opportunity to apply full sustainability in the whole biosphere, i.e., the complete set of SPs informed by the PBs as impact guides within the earth system, as a starting point for their strategic planning, action steps, and innovation. In line with the FSSD, this is enabled by highlighting the enterprise risk and the potential self-beneficial business case for gradually becoming part of global solutions rather than problems, as a function of proactive management of escalating changes in resource costs, tax, insurance, opportunity costs, and markets, plus a set of logical guidelines for how to plan ahead accordingly.

DETAILED ANALYSIS OF PBA WITH THE FSSD

To more fully elucidate the specific utility and implications of a combined PBA and FSSD approach, with a focus on how the SPs can provide insight and guidance for strategic actions in the face of PBs, we have analyzed the inter-relationships between specific proposed planetary boundary assessment metrics and the SPs at the second level of the above described FSSD.

Climate change, CO2 concentration in the atmosphere < 350 ppm and/or a maximum change of +1 Wm-2 in radiative forcing.

This boundary refers partly to the first of the FSSD's SPs, to put a halt to systematic concentration increases of matter from the lithosphere, i.e., materials that are net introduced into the biosphere. Because of the law of matter conservation, this principle can, in the end, only be complied with either by zero use of fossil fuels, or through a balanced offsetting of flows of CO_2 waste emissions through redeposits of some form. For the individual organization or sector, this means a vision of a complete stop in emitting fossil CO_2 and other greenhouse gases, and a systematic program to get to this point. This can be made part of organizational planning without knowing the exact planetary boundary tipping point for atmospheric greenhouse gas levels. However, also in violation of the third of the SPs, the degradation of land by physical means, e.g., slash-and-burn forestry, adds CO_2 to the atmosphere and diminishes CO_2 fixing capacity. This means a vision of phasing out many different kinds of actions that contribute to such emissions, e.g., purchase of wood from poorly managed forests, strip-mining without refurnishing of biotopes after mining, etc. This same line of reasoning, showing how transparent SPs reveal the need for actions and practices that are not directly guided by the PBA, is applied to the remaining PBs.

Ocean acidification, i.e., mean surface seawater saturation state with respect to aragonite > 80% of preindustrial levels.

While the current PB in this area focuses on aragonite levels and potential impacts of acidification on dissolving $CaCO_3$ in marine organisms, the FSSD provides a broader view of addressing diverse ocean acidification mechanisms. This boundary reflects a combination of SPs 1 to 3, because acidification may occur from emissions of compounds like CO_2, SO_x, and NO_x (SP 1 and 2), as well as through erosion and drainage from acidified land in which poor management routines (SP 3) add to the problem by not addressing soil pH balance. Visions that include no contribution at all to this problem should be on the table, with accompanying strategic business programs to get there. Complete strategic efforts would take into account all three of these fundamental mechanisms, SP 1 to 3 informed issues, when being formulated.

Stratospheric ozone, < 5% reduction in O3 concentration from preindustrial level of 290 Dobson Units.

Ozone destruction is due to an accumulation of other chemicals in the stratosphere, i.e., it reflects SP 2, substances produced by society, which may inform a planetary boundary that the authors of the PBA concept intend to come back to in later studies, that of chemical pollution. In brief, planning toward compliance with SP 2 implies an almost complete end to the emitting of Persistent Organic Pollutants (POPs) and other compounds increasing in concentrations in the biosphere. The strategies to move toward not contributing to the violation of SP 2 vary depending on cumulated regional and global emissions, as well as on the qualities of the compounds, e.g., degradability.

Biogeochemical nitrogen (N) cycle, limit industrial and agricultural fixation of N2 to 35 Tg N yr-1.

This is, again, a boundary that relates to SP 2. It differs from the first three PBs in that it is a limitation of a flow and not a state.

Phosphorus (P) cycle, annual P inflow to oceans not to exceed 10 times the natural background weathering of P, i.e. 10 Tg P yr-1.

This reflects SP 1, i.e., emission of a substance that is originally sourced from lithosphere deposits. However, phosphate emissions into the sea are not only a sustainability problem related to eutrophy, from a violation of the first of the SPs, but also are a waste of a limited resource that is essential for life itself for coming generations. The man-made excess flow of phosphates from the lithosphere to the ocean represents a depletion of the ore reserves of a life-supporting mineral that can probably not be replaced by any other. Thus, we degrade by physical means (SP 3) the ability of the earth system to sustain civilization.

Global freshwater use, < 4000 km³ yr-1 of consumptive use of runoff resources.

This boundary, as it is stated, relates mainly to SP 3, i.e., we should not use so much freshwater that the global system, including freshwater reserves, is systematically degraded. However, from a full sustainability point of view, freshwater in general needs to be considered from all four SPs. The first two principles speak to the need of safeguarding freshwater reserves from systematically increased concentrations of matter from the lithosphere and society-produced chemicals. The third principle is about improving the management of ecosystems such that the availability of freshwater will not systematically decline, which entails more than not using too much of it. Finally, sufficient freshwater availability needs to be secured globally by wise and responsible use of political and economic power (SP 4).

Land system change, < 15 % of the ice-free land surface converted to cropland.

This boundary is an estimate of the amount of uncultivated land needed to sustain sufficient regulatory capacities of the Earth System and biodiversity. It clearly reflects the framework's SP 3. From a sustainability point of view, we need not only to safeguard uncultivated land, but also forestry, cropland, fisheries, and land use for other purposes, e.g., avoiding destructive urban sprawl. The latter is increasingly important because such coupled human-natural systems have already become significant and these cultivated ecosystems are under gradual decline with, e.g., eroding topsoil layers, nutrient imbalance, and loss of stabilizing biodiversity. The result is partly a declining potential to sustain civilization from the cropland we have, and partly a drive to exploit more wild ecosystems to compensate for the losses. From a sustainability point of view, it seems relevant to aim at no further irreversible physical damage to all ecosystems.

Biodiversity loss, annual rate of < 10 extinctions per million species.
This boundary relates to SPs 1 to 3, the most obvious being principle 3 because most biodiversity loss so far is due to physical mismanagement, i.e., historically there is a strong coupling to the "land system change" variable. However, the risk of declining biodiversity is not only about physical management routines such as overharvesting and encroaching on ecosystems to give room for infrastructure and for other reasons. It is also about pollution and therefore this boundary also relates to SPs 1 and 2.

Two additional PBs for which a limit has not yet been determined are atmospheric aerosol loading and chemical pollution, respectively. These boundaries relate mainly to SPs 1 and 2 and to some degree to SP 3, regarding some aerosols from soil erosion and considering finite reserves of some chemicals or elements. Regarding chemical pollution, the authors of the PBA sincerely doubt that it will ever be possible to define a single boundary, given the many chemicals used and their interactions. However, regarding indicators on pollution, there is a useful study (Azar et al. 1996) based on the FSSD approach. For example, materials from the lithosphere can be managed from a sustainability point of view by the use of indicators derived with SP 1 in mind. Through comparisons of natural flows of lithosphere materials, from weathering and volcano eruptions, on the one hand, and anthropogenic flows on the other, e.g., mining, it has been possible to rank the materials concerning their potential for causing future concentration increases in the ecosystem. This provides guidance, at the level of first approximation, with regard to material substitution in redesign. One concrete example regarding both the first and second of the FSSD's SPs is provided by the Electrolux example described previously.

DISCUSSION AND CONCLUSIONS

The FSSD includes basic principles for sustainability and guidelines for their strategic and systematic application. The FSSD is elaborated from the recognition that systemic actions violating these sustainability principles (SPs) will, at some point, lead to overreaching planetary boundaries (PBs), be they those quantified in the planetary boundary approach (PBA), or others as yet undefined. This relationship highlights the potential synergies between the two concepts. We have shown that the underlying mechanisms that push civilization toward or beyond PBs are in fact violations of the presented SPs. Furthermore, and to that end, we have shown that the PBA, for analyses as well as for use in strategic planning, would gain from allowing those principles to be transparent rather than hidden, and vice versa; the FSSD used without an idea of the boundaries for further violation of the SPs would imply a lost opportunity, e.g., for appropriately prioritizing based on the most current knowledge on critical planet-scale impacts.

Thus, (1) explicit sustainability principles as described can inform and delineate the range of actions that must be taken to fully address known and unknown PBs. (2) Within the context of the FSSD and when PBs are known, the knowledge of the current values of the PB variables and their rates of change helps clarify the relative urgency of actions, and thus offers a basis for prioritization. (3) Targeted and prioritized actions for known PBs must be assessed against the SPs to minimize the development of new sustainability challenges or impact on other PBs. (4) Where clarity on PBs and tipping points do not yet exist, or are not likely to exist, then a general strategy of substitutions guided by the FSSD is needed. (5) The FSSD approach specifically includes considerations of the social sustainability dimension and how the ecological and social systems are interrelated, something not currently included in the PBA. (6) Finally, when known PBs are embedded within the FSSD, individual organizations can act systemically to move away from contributing to the risk of global society reaching tipping points, even in the absence of a single global governing body or consensus on specific cause and effect chains. The FSSD provides a science-based framework that enables individual organizations to act systemically by moving strategically toward compliance with the SPs and PBs, and to do so from a self-beneficial point of view thereby avoiding dynamically increasing risks and opportunity costs from continuous contributions to the violation of the SPs. This offers possibilities for societal development over and above legislative policies, and at the same time as organizations move ahead by use of the FSSD and the PBA, they may serve as role models and leverage points for more active societal policies.

Item 6 should be highlighted. Given the current global situation, i.e., rapidly increasing deviations in many known PB-variables because of violations of basic SPs, and recognition of the enormous gap in knowledge between known and unknown PBs, businesses, nongovernmental organizations, and governments should not wait to take appropriate and systemic actions for sustainability until more critical PBs are known. Society must increasingly avoid destructive debates regarding when enough is known about any given PB to act. The FSSD provides a vehicle for a constructive dialogue and approach, enhanced by known PBs.

Successful action toward sustainability requires that individual actors have strategic pathways with appropriate and inherent incentives for systemic action toward sustainability (Ostrom 2009, 2012, Basile et al. 2011). Thus, the PBA must address the individual actor in an adequate way to be effective. If not, the PBA may even enhance the problems we are witnessing today. Negotiators across the planet might focus even more on identifying singular causes of negative impacts within some PBs, rather than seek to address PB challenges systematically and by designing the problem out of the system. The risk is exemplified by geopolitical negotiations on climate change where the logic seems to be that the nation that successfully negotiates its way to become the last to leave the fossil-fuel era would be the big winner. However, when combined with the FSSD, individual organizations can have confidence that they are moving strategically in a sustainable direction, and the PBA can then provide increasing insight into prioritization for action both in their own organization and when acting as partners in various sectors and institutional groups. Indeed, the FSSD provides a vehicle for individual and institutional planners who decide that it is in their best interest to actively avoid being part of the problems highlighted by PBs at all.

Empowering individual actors is required for success for another key reason, regional boundaries. Regional boundaries are not considered explicitly in the PBA. Examples of regional boundaries include regional differences in the buffering capacity for acid rain or in the capacity of soils to denitrify fertilizers, thereby avoiding accumulation of acidic or nitrogenous compounds, respectively. In this context, regional differences do not only occur by natural reasons. Differences are also due to the combination of actions of others in the same region. To that end, sustainable development requires that each actor takes into account not only the PBs, but also regional boundaries in combination with regional differences of load, and vice versa. The FSSD's first two principles instruct organizations to not contribute to increasing concentrations of pollutants, and the critical boundaries differ depending on the region. The same is true for certain aspects of the third principle, e.g., regarding overharvesting where sustainability boundaries are different in different regions. This dimension of the FSSD provides a bridge between the PBA's planet-scale boundaries and metrics and local and regional strategies and actions.

In conclusion, the FSSD and PB approaches can be used in parallel to arrive at critical and synergistic results, i.e., real, measurable progress toward sustainability at all scales, from individual to global. PBs highlight a basic shift in today's complex global social-ecological system. We are approaching global boundaries beyond which we can expect system failures and breakdown in life-supporting earth-system services. The PBs, both individually and as a whole, represent critical guiding goals at the highest level in the five-level model of the FSSD, i.e., level 1 for the Earth system. The FSSD provides a framework for moving systematically toward remaining within PBs while undertaking socioeconomic development and innovation. The combined use opens up for strategic management of the problems we know relatively well, e.g., by prioritizing based on the acuteness of such violations where we are close to trespassing PBs. It also opens up for strategic management of such violations where the PBs are still uncertain, not yet known at all, or impossible already from a theoretical point of view to present in terms of PBs. And, also, it opens up for new research where the calculation of more PBs can be informed by the FSSD, e.g., PBs related to the third and fourth SPs. The planetary boundary work is important and should be used to support strategic planning toward a robust, principled definition of sustainability. A combined research and application approach is needed.

LITERATURE CITED

Andersson, K., M. H. Eide, U. Lundqvist, and B. Mattsson. 1998. The feasibility of including sustainability in LCA for product development. *Journal of Cleaner Production* 6 (3-4):289-298.

Azar, C., J. Holmberg, and K. Lindgren. 1996. Socio-ecological indicators for sustainability. *Ecological Economics* 18:89-112. http://dx.doi.org/10.1016/0921-8009(96)00028-6

Basile, G., G. Broman, and K.-H. Robèrt. 2011. A systems-based approach to sustainable enterprise: requirements, utility and limits. Pages 3-28 *in* S. McNall, J. Hershauer, and G. Basile, editors. *The business of sustainability*, Vol. 1., Praeger Press, New York, New York, USA.

Broman G., J. Holmberg, and K.-H. Robèrt. 2000. Simplicity without reduction: thinking upstream towards the sustainable society. *Interfaces* 30:13-25. http://dx.doi.org/10.1287/inte.30.3.13.11662

Byggeth, S. H., G. Broman, and K.-H. Robèrt. 2007. A method for sustainable product development based on a modular system of guiding questions. *Journal of Cleaner Production* 15:1-11. http://dx.doi.org/10.1016/j.jclepro.2006.02.007

Clausewitz, C. 1832. *Vom kriege.* Dümmlers Verlag, Berlin, Germany.

Esty, D. C., and M. E. Porter. 1998. Industrial ecology and competitiveness: strategies implications for the firm. *Journal of Industrial Ecology* 2:35-43. http://dx.doi.org/10.1162/jiec.1998.2.1.35

Gordon, S. 2004. *The natural step along Whistler's journey*. Whistler2020, Whistler, British Columbia, Canada. [online] URL: http://www.whistler2020.ca/whistler/site/genericPage.acds?context=1967914&instanceid=1967915

Holmberg, J., U. Lundqvist, K.-H. Robèrt, and M. Wackernagel. 1999. The ecological footprint from a systems perspective of sustainability. *International Journal of Sustainable Development and World Ecology* 6:17-33. http://dx.doi.org/10.1080/13504509.1999.9728469

Holmberg, J., and K.-H. Robèrt. 2000. Backcasting - a framework for strategic planning. *International Journal of Sustainable Development and World Ecology* 7:291-308. http://dx.doi.org/10.1080/13504500009470049

Korhonen, J. 2004. Industrial ecology in the strategic sustainable development model: strategic applications of industrial ecology. *Journal of Cleaner Production* 12:809-823. http://dx.doi.org/10.1016/j.jclepro.2004.02.026

MacDonald, J. P. 2005. Strategic sustainable development using the ISO 14001 standard. *Journal of Cleaner Production* 13:631-644. http://dx.doi.org/10.1016/j.jclepro.2003.06.001

Matsushita Electric Industrial. 2002. *Matsushita's environmental sustainability report 2002*. Matsushita Electric Industrial, Osaka, Japan.

Mintzberg, H., B. Ahlstrand, and J. Lampel. 1998. *Strategy safari: a guided tour through the wilds of strategic management*. Free Press, New York, New York, USA.

Ny, H., S. Hallstedt, K.-H. Robèrt, and G. Broman. 2008. Introducing templates for sustainable product development through a case study of televisions at Matsushita Electric Group. *Journal of Industrial Ecology* 12:600-623. http://dx.doi.org/10.1111/j.1530-9290.2008.00061.x

Ny, H., J. P. MacDonald, G. Broman, R.Yamamoto, and K.-H. Robèrt. 2006. Sustainability constraints as system boundaries: an approach to making life-cycle management strategic. *Journal of Industrial Ecology* 10:61-77. http://dx.doi.org/10.1162/108819806775545349

Ostrom, E. 2009. A general framework for analyzing sustainability of social-ecological systems. *Science* 325:419-422 http://dx.doi.org/10.1126/science.1172133

Ostrom, E. 2012. Nested externalities and polycentric institutions: must we wait for global solutions to climate change before taking actions at other scales? *Economic Theory* 49:353-369.

Robèrt, K.-H. 2000. Tools and concepts for sustainable development, how do they relate to a general framework for sustainable development, and to each other? *Journal of Cleaner Production* 8:243-254. http://dx.doi.org/10.1016/S0959-6526(00)00011-1

Robèrt, K.-H., G. Broman, D. Waldron, H. Ny, S. Byggeth, D. Cook, L. Johansson, J. Oldmark, G. Basile, H. Haraldsson, J. MacDonald, B. Moore, T. Connell, and M. Missimer. 2012. *Sustainability handbook*. Studentlitteratur, Lund, Sweden.

Robèrt, K.-H., H. E. Daly, P. A. Hawken, and J. Holmberg. 1997. A compass for sustainable development. *International Journal of Sustainable Development and World Ecology* 4:79-92. http://dx.doi.org/10.1080/13504509709469945

Robèrt, K.-H., J. Holmberg, and E. U. V. Weizsacker. 2000. Factor X for subtle policy-making: objectives, potentials and obstacles. *Greener Management International* 31:25-38.

Robèrt K.-H., B. Schmidt-Bleek, J. Aloisi de Larderel, G. Basile, J. L. Jansen, R. Kuehr, P. Price Thomas, M. Suzuki, P. Hawken, and M. Wackernagel. 2002. Strategic sustainable development - selection, design and synergies of applied tools. *Journal of Cleaner Production* 10:197-214. http://dx.doi.org/10.1016/S0959-6526(01)00061-0

Rockström, J., W. Steffen, K. Noone, Å. Persson, F. S. Chapin, III, E. Lambin, T. M. Lenton, M. Scheffer, C. Folke, H. Schellnhuber, B. Nykvist, C. A. De Wit, T. Hughes, S. van der Leeuw, H. Rodhe, S. Sörlin, P. K. Snyder, R. Costanza, U. Svedin, M. Falkenmark, L. Karlberg, R. W. Corell, V. J. Fabry, J. Hansen, B. Walker, D. Liverman, K. Richardson, P. Crutzen, and J. Foley. 2009. Planetary boundaries: exploring the safe operating space for humanity. *Ecology and Society* 14(2): 32. [online] URL: http://www.ecologyandsociety.org/vol14/iss2/art32/

Vancouver Organizing Committee (VANOC). 2010. *Vancouver 2010 Sustainability Report*. VANOC, Vancouver, British Columbia, Canada. [online] URL: http://www.olympic.org/Documents/Games_Vancouver_2010/VANOC_Sustainability_Report-EN.pdf

Waage, S. A., K. Geiser, F. Irwin, A. B. Weissman, M. D. Bertolucci, P. Fisk, G. Basile, S. Cowan, H. Cauley, and A. McPherson. 2005. Fitting together the building blocks for sustainability: a revised model for integrating ecological, social, and financial factors into business decision-making. *Journal of Cleaner Production* 13:1145-1163. http://dx.doi.org/10.1016/j.jclepro.2004.06.003

Whistler Municipality. 2007. *Whistler 2020*. Whistler Municipality, Whistler, British Columbia, Canada.

World Commission on Environment and Development. 1987. *Our common future*. Oxford University Press, Oxford, UK.