

Monitoring Sustainability and Targeting Interventions: Indicators, Planetary Boundaries, Benefits and Costs

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Abstract: This article shows how sustainability indicators (SIs) which have proliferated, and down-scaled planetary boundaries (DPBs) which have recently emerged, can be used to target remedial interventions. I offer an integrative analysis drawing upon the existing literature, challenging, clarifying, and amending it in some ways, and extending it with new insights. The exposition is couched in the example of pollution control, but the analysis also applies to resource management with only modest amendments. Key conclusions are summarized. (i) In a default case where damage is indifferent to location within the problem shed and transactions costs are trivial, minimizing abatement costs requires that all units face the same marginal price of emissions and can be implemented by price setting at the jurisdictional level or cap and trade in pollution reduction credits. Larger geographic scale tends to reduce the average cost of abatement, an argument for coordination at the problem-shed level. Deviations from the default policy may be appropriate for addressing large point sources and local hot spots where damage is concentrated. (ii) A framework winnowing the proliferation of SIs includes the following principles: for quantitative target setting, SIs should address sustainability in its long-term context; SIs should be measured in ratio scale, whereas ordinal-scale SIs are common; and SIs should be selected for their usefulness in mapping the relationships among emissions, ambient concentrations, and damage. (iii) Target setting requires science-based empirical relationships and social values to assess trade-offs between abatement and its opportunity costs and suggest upper limits on tolerable damage. (iv) PBs that address global public goods can usefully be downscaled to set abatement targets. The PBs are science based and, in their original form, propose replacing social values with imperatives: violating the PB will doom the planet, which is unacceptable given any plausible value system. Given that $PB = \sum DPB$ over all jurisdictions, global trading of credits would minimize costs of honoring the PB. Trade among a willing subset of jurisdictions could minimize the costs of meeting its aggregate DPB. (v) In contrast to most SI approaches, a cost–benefit (CB) approach can deal with substitutability and complementarity among sustainability objectives and evaluate multi-component policies. Net benefits are maximized when the marginal cost of abatement equals the marginal benefit for all units in the problem shed. This can be attained by price setting at the jurisdictional level or trade in credits. (vi) A major advantage of the CB approach is its well-defined relationship to weak sustainability. However, its value measures over-weight the preferences of the well-off. Equity considerations suggest relief from strict CB criteria in the case of essentials such as human health and nutrition, and subsidization by rich countries of sustainability projects in low-income countries.

Keywords: sustainability indicators; planetary boundaries; monitoring; targeting; downscaled planetary boundaries; weak sustainability; strong sustainability; cost minimization; cost–benefit approach



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1. Introduction

Weak sustainability (WS) posits that welfare can be sustained through the generations so long as inclusive wealth (IW) is non-diminishing [1–3]. IW is an aggregate construct, and purposefully so: the whole point is that different kinds of capital are substitutable so that increases in one kind can compensate for decreases in another [4–6]. Tracking IW provides

an indicator of WS but does not identify remedial interventions, which must be chosen and targeted at the micro scale. Hence the need for sustainability indicators (SIs). Strong sustainability (SS) is focused from the outset on specific critical natural resources [7,8], such that some SIs support direct interpretation in terms of SS.

Sustainability indicators have proliferated beyond expectations in recent years. A recent study [9] identified more than 240 different indicators of sustainable development [10,11] and used more than 140 of them to develop composite metrics. The USEPA [12,13] winnowed its list down to 83 indicators focused on sustainability per se—sustaining environmental services, ES, and the natural capital that produces them—i.e., omitting those addressed to wellbeing aspects of sustainable development [14]. Articles addressing SIs and how to use them in policy and management appear in a wide range of journals addressed to sustainability and related concerns [15,16] and at least two journals now specialize in such indicators: *Environmental and Sustainability Indicators* and *Ecological Indicators*. SIs vary widely in several dimensions: focus on sustainable development or sustainability per se; the object of measurement and tracking, emissions (or extraction), ambient conditions, or impact on human and natural systems; ordinal, cardinal, or ratio measurement scale; and even presentation style where dashboards of various kinds compete with more prosaic tables of data. The data overload inherent in literally hundreds of SIs has motivated efforts of many kinds to systematize SIs: organize them around categories, and/or themes; employ cluster analysis, principal components analysis, etc., to let the data speak regarding groupings of indicators; and analyses to compare and rank sustainability performance of regions or localities in broad thematic groupings [17,18].

More recently, a literature on downscaled planetary boundaries (DPBs) has emerged, comparing the performance of local jurisdictions with calculated DPB shares for each of the PBs [19,20]. Proliferation of DPBs is hardly a concern given that the literature recognizes only nine PBs. However, DPBs raise their own concerns. For example, the Rockstrom et al. [21] proposition of bright-line PBs that render debate about values irrelevant by asserting that violating them would cause intolerable harm to human prospects is undermined by the more recent Steffen et al. [22] recognition that, more realistically, PBs are fuzzy, a zone of uncertainty lies between the green and red zones, and collapse and recovery are uncertain prospects.

Here we examine the foundations of monitoring for sustainability and setting targets for enhancement, at scales ranging from the individual unit (a plant, a firm, or a consumer) to the jurisdiction, problem shed, and planet. The research questions include (i) to begin, for a given emissions target, how might abatement costs be minimized? How does scale influence abatement costs, and what does that suggest regarding the ideal scale for jurisdiction? (ii) How can and should targets for interventions be set? (iii) How can SIs help in this process? There are a large number of SIs that differ in several ways, and it is easy to get lost in the weeds: how do we winnow the list and make the best use of SIs in policy and management? (iv) DPBs are relatively few in number, but the challenge of winnowing the list applies to DPBs, too. Which PBs make promising candidates for downscaling, and how might DPBs be used in targeting? (v) In what ways does a cost–benefit (CB) framework help in targeting? What restraints on influence of CB on policy and management might be ethically appropriate? To address these questions succinctly yet fairly comprehensively, I offer an integrative analysis drawing upon the existing literature, challenging, clarifying, and amending it in some ways, and extending it with new insights regarding the relationship between abatement costs and the geographic scale of jurisdiction; the use of SIs and DPBs in monitoring and targeting; the need for SIs to help implement the CB framework, counter-balanced to some extent by the policy fragmentation that seems to be encouraged by the proliferation of SIs; and the irrelevance of benefit estimates in DPB approaches, which treat honoring a PB as an imperative rather than a choice. Nevertheless, cost minimization remains relevant in DPB approaches, suggesting a role for price-based and cap-and-trade policy instruments.

It is common to think of sustainability as involving two distinct kinds of threats: we might run out of important resources [23,24], and our environment might be blighted by pollution. However, these threats are really not so different. If the waste assimilation capacity of the environment is a limited resource [25], we can conceptualize the problem much as we would think about a forest management problem: both are renewable resources that can be undermined by excessive exploitation. The analyses and insights offered here have implications for both kinds of sustainability challenges.

2. Methods and Materials

The overall objective is to offer a critical examination of the foundations of monitoring for sustainability and setting targets for improvement, at scales ranging from the individual unit (a plant, a firm, or a consumer) to the jurisdiction, problem shed, and planet. This is a conceptual enquiry, but one that is unrelentingly applied in its orientation and conclusions. The analysis is focused on a stylized pollution abatement case, but it should be noted that the other major sustainability issue, resource depletion, can be addressed with simple modifications (substitute extraction for emissions, remaining stock for ambient concentration, and resource scarcity for damage). This should present no surprise: back in 1972, Meadows et al. framed pollution problems as allocation of limited waste assimilation capacity [25].

We focus mostly on the default case with multiple polluters and receptors scattered throughout a problem shed such that damage is indifferent to location within the problem shed. Two plausible exceptions are caveated below, and it is noted that they can be addressed as special cases while the conclusions developed here are implemented for the broad swathe of cases to which the default assumption applies.

2.1. Key Concepts and Definitions

Suppose a baseline with no policy regarding a particular kind of emissions that are ignored or recognized but thought harmless. Then, signs of damage generate alarm and lead to monitoring damage. Research identifies the ambient concentration of a particular pollutant as a driver, and a program to reduce and control emissions is implemented. Thereafter, ambient concentrations and damage are monitored for evaluation and on-going improvement of the program, and emissions are monitored for compliance. Starting from scratch, all of this takes a lot of research, and may result in a new program of abatement. More commonly, the process starts somewhere in the middle: policy makers and managers have a working knowledge of the basic dimensions of the problem and the relationships that matter, and now are trying to design and implement a satisfactory program to monitor environmental and health outcomes, and target improvements. They confront a plethora of indicators that vary in kind, quality, and relevance [16]. This article suggests ways to make sense of it all.

Key concepts include

- $s(t)$: the time path of the flow of environmental service (ES), s , normalized so that society benefits when $s(t)$ is increased, and sustainability is enhanced *ceteris paribus* if the level of sustainable $s(t)$ is increased. ESs include providing raw materials, natural resource services, and amenities of various kinds, and can be enhanced by abating various pollutants and conserving natural capital, desired landscapes, ecosystems, etc. In what follows, pollution abatement serves as the exemplar, so the ES is a reduction in ambient concentration as might result from reduced emissions. However, the analysis can be applied to conservation problems with only modest amendments.
- $e(t)$: the time path of emissions.
- $d(t)$: the time stream of damage to human and natural systems, as may occur when $s(t)$ is lower than desirable.
- The posited relationship of $e(t)$, $s(t)$, and $d(t)$: abatement policy and management are conceived as typically involving attempts to increase $s(t)$ by reducing $e(t)$ in order to reduce $d(t)$.

- Households, plants, or firms, i : units that generate $e(t)$ and, if so motivated, can provide $s(t)$. Units may also be receptors, generating emissions and suffering damage but not necessarily in the same proportions.
- Economic sectors, j , e.g., forest products, in which units operate.
- Jurisdictions, k , that might have authority over the relevant aspects of environmental policy within their geographic boundaries.
- Units providing ES and beneficiaries are dispersed across the landscape such that policy and management of a particular ES may involve several s_{ijk} , i.e., several polluting units, quite likely several economic sectors, and perhaps several jurisdictions.
- Problem sheds, which are defined by relevant natural boundaries that may be unique for a particular ES. For example, the problem shed for water quality in a lake is the drainage basin but for instream water quality the problem shed is the watershed. Air pollution may be relevant in a watershed, but its problem shed is the airshed which most likely is not coterminous with the watershed.
- SI: sustainability indicator. One might expect SIs to address ambient $s(t)$, in which case, the SI is measured on a scale that increases monotonically with the level of $s(t)$. However, published SIs also include some that track emissions and some that address damage, as well as yet others focused more on wellbeing broadly defined.
- PB: planetary boundary, as defined by Rockstrom et al. [21] and amended by Steffen et al. [22].
- SOS: safe operating space, i.e., the safe space for human activity within a PB.
- DPB: downscaled PB. $DPB = PB / \text{global denominator}$, where the denominator may be population, GDP, or some other relevant variable. The DPB is treated as a norm, to which local impact in terms of downscaled local footprint, DLF, may be compared. The same variable is used in the denominator for DPB and DLF.
- $w(t)$: the time path of human welfare. Weak sustainability is attained when $w(t)$ is non-decreasing into the distant future.
- C and B : cost and benefit defined as welfare change metrics. If we know the time path of costs, $C(t)$, and benefits, $B(t)$, of a policy, we can predict its influence on the welfare stream, $w(t)$.
- c and b : marginal cost and marginal benefit, concepts essential to cost minimization and net benefit maximization strategies.

2.2. Approach

I begin by deriving necessary conditions for cost minimization, an obvious objective given any abatement target, for the default case. However, it remains important to set the right abatement target. This requires two distinct kinds of information, (i) science-based mapping of the relationships among emissions, ambient concentrations, and damage to human and natural systems, and (ii) human and social values, to evaluate the inevitable trade-offs and determine the limits to acceptable damage. SIs and DPBs are evaluated in terms of their potential contribution to assembling and organizing this information. Because not all sustainability indicators and downscaled PBs are useful in this context, the characteristics of useful SIs and DPBs are identified. Then I outline a cost–benefit framework for target setting and evaluate its advantages and limitations. Among other things, the conclusions address equity considerations in general, including the equity implications of the cost–benefit approach.

2.3. Caveats

Two caveats are pertinent. First, the assumption that polluters and receptors are dispersed across the landscape sets aside two kinds of special cases—the single megapolluter, e.g., a large coal-fired power plant, and the hot spot, i.e., a relatively small geographic space with an alarmingly high concentration of pollutant(s) and incidence of damage—which are best addressed individually with targeted remedies. Furthermore, the existence of a few large point sources and/or hotspots managed with targeted remedies

does not rule out management at the problem-shed level for the many dispersed polluters and receptors [26].

Second, given that many of the issues addressed involve abatement-cost savings from increasing scale, there is the non-trivial possibility that the need for coordination and the transactions costs of so doing may also increase with scale. I do not address transactions costs here, implicitly assuming that (i) while they may reduce somewhat the realized gains from increasing scale, they are unlikely to be so large as to eliminate those gains, and (ii) the practical work of coordination will include systematic efforts to reduce transactions costs, ideally by institutional design that widely distributes the gains from coordination.

3. Results and Discussion

3.1. Minimizing Abatement Costs

3.1.1. For an Economic Sector

Assume a target has been set for abatement of a pollutant $s_{jk}(t)$ released by a particular economic sector j in jurisdiction k . To simplify the exposition, the (t) denoting a time path is suppressed but remains implicit. The regulator can control emissions from units i in sector j in jurisdiction k . So, given a science-based mapping of emissions and ambient pollutant concentrations, she sets a target for total emissions $T(e_{jk}) = e'_{jk}$ corresponding to the desired level s'_k of ambient ES. There are several strategies she might invoke to motivate abatement at the unit level: perhaps assign each unit an equal weighted share of the abatement target (weighted, e.g., by the unit's production capacity) or an equal proportional target, e.g., $x\%$ of the unit's baseline emissions. However, suppose there is dispersion of abatement costs among the many providers of e_i in j so that some providers are more cost efficient than others [27,28]. Minimize total abatement costs, C , subject to the constraint that total emissions equal the target emissions, $T = e'_{jk}$, for the jurisdiction:

$$\text{Min } \sum C_{ij}(e_i) + \lambda(\sum e_i - e'_{jk}) \quad (1)$$

First-order condition: $c_i(e_i) = \lambda$, $\forall i$ in j and k .

That is, to minimize total abatement costs for a given target level of abatement, the price of (i.e., incentive for) abatement should be set at λ for all units i in j and k , that is, equal to the marginal abatement cost. This can be accomplished by administrative pricing or via trade in pollution reduction credits [27,28], and an extensive literature has emphasized an important difference between these instruments: administrative pricing requires that the regulator possess or discover information on unit-level costs, whereas costs are revealed in cap-and-trade markets [29]. Other assignments of abatement responsibility, e.g., a fixed percentage reduction from baseline emissions, would result in higher total costs for the same level of aggregate abatement. A strategy that decreases aggregate abatement costs for a given target thereby increases the sustainable level of welfare $w_j(t)$ in sector j .

3.1.2. For a Jurisdiction

It is often the case that multiple economic sectors are responsible for a given pollutant in a jurisdiction. A multiplicity of sectors suggests a greater heterogeneity of technologies in k , which suggests greater dispersion of abatement costs. Suppose the regulator can control emissions from units i in sectors j in jurisdiction k . The regulator seeks to minimize abatement costs and thus increase the sustainable level of welfare $w(t)$. So, minimize total abatement costs, C , subject to the constraint that total emissions equal the target emissions, $T = e'_k$, for the jurisdiction:

$$\text{Min } \sum C_{ij}(e_{ij}) + \lambda(\sum e_{ij} - e'_k) \quad (2)$$

First-order condition: $c_{ij}(e_{ij}) = \lambda$, $\forall i$ and j in k .

That is, marginal abatement cost = λ , the shadow price of emissions for all units and sectors in k . To the extent that abatement costs vary among economic sectors, this solution will reduce total abatement costs relative to a strategy of regulating sector by sector.

3.1.3. For the Problem Shed

Now, assume that emissions from all locations within the problem shed are equally damaging. Again, abatement cost minimization for the problem shed requires that each provider of a given category of environmental services in the problem shed face the same incentive for abatement. Suppose the regulator can control emissions from units i in sectors j in jurisdictions k within the geographic boundaries of the problem shed. Minimize total abatement costs, C , subject to the constraint that total emissions equal the target emissions, $T = e'$, for the problem shed:

$$\text{Min } \sum C_{ijk}(e_{ijk}) + \lambda(\sum e_{ijk} - e') \quad (3)$$

First-order condition: $c_{ijk}(e_{ijk}) = \lambda$, $\forall i, j$ and k in the problem shed.

Coordination at the problem-shed level is likely to reduce the average cost of abatement given that larger jurisdictional scale is likely to increase heterogeneity in natural conditions, e.g., elevation, slope, precipitation, etc. For problem sheds of less than global dimensions, the gains from coordination may be exhausted at the problem-shed level, because marginal social damage may vary across problem sheds.

The assumption that damage is indifferent to location within a problem shed is not as limiting as might seem at first glance. Systematic differences—e.g., upstream vs. downstream, and distance from stream bank—often can be handled with systematic science-based adjustments, e.g., sediment delivery ratios that normalize the contributions of runoff from different farm fields to instream pollution [30].

3.1.4. For a Global Public Good

For a global public good, the problem shed is global. Consider abatement cost for a category of ES, s_c , where c is atmospheric carbon, the abatement of which is a global public good. The regulator seeks to enhance this service by reducing emissions, e_c .

$$\text{Minimize } \sum C_{ij}(e_{cij}) + \lambda(\sum e_{cij} - e_c) \quad (4)$$

First-order condition: $c(e_{cij}) = \lambda$, $\forall i, j$ and k worldwide.

Thus, other things equal, abatement incentives should be equal for all providers globally, as might result from a universal administered carbon price or global carbon cap and trade. However, gross inequality at the global scale suggests caveats to these kinds of sweeping conclusions.

3.1.5. Generalizing the Proposition That Gains from Cost Minimization Tend to Increase with Scale

Define scale as increasing in (i) the number of plants or firms i in a sector, (ii) the number of sectors j , and (iii) the number of jurisdictions k , in which regulation is coordinated, but is bounded by the dimensions of the problem shed. Thus, scale ranges from the smallest, a single plant or household, to the largest, all of the providers of s in the whole problem shed. Increasing scale increases the number of units providing a given ES. If we think of each unit as drawing from a given distribution of abatement costs, an increasing number of units increases sample size, but that alone does not increase the dispersion of abatement costs. Similarly, if we increase scale by replicating the baseline situation, the dispersion of abatement costs will not increase. However, increasing scale up to the whole problem shed is not a matter of replication. Rather, it is likely to increase heterogeneity of units and operating conditions, tending to increase the dispersion of unit-level abatement costs. Cases where damage, normalized if necessary, is indifferent to location within a problem shed but abatement costs are sensitive to local conditions are plausible and quite likely the norm.

With increasing dispersion of abatement costs among units, there is increasing opportunity to engage low-cost providers of abatement, thereby increasing the gains from cost-minimizing assignment of abatement responsibility. If welfare $w(t)$ increases mono-

tonically with $s(t)$, sustainable $w(t)$ increases as the marginal cost, $c(e(t))$, of abatement is reduced. With appropriate incentives, lower-cost units will be willing to do more than their proportional share of abatement, reducing total abatement cost to achieve a given target level $T = e'$. With increasing scale and dispersion of abatement costs at the unit level, the gains from cost-minimizing assignment of abatement responsibility by equalizing incentives throughout the problem shed tend to increase. For global public goods the whole planet is the ultimate problem shed, and it is likely that planetary scale and heterogeneity would reward global coordination with substantial opportunities for cost-reducing allocations of abatement responsibility.

3.1.6. The Case of Multiple Distinct Kinds of ES

The cost-minimizing principles deduced above remain helpful in the case of multiple ES. However, proliferation of ES introduces complications as well as opportunities [26].

If the different s are independent of each other in production and demand, and if they are widely dispersed across the landscape, the conclusions above hold for each of the s . However, these assumptions are quite restrictive. Consider some cases where one or more of these assumptions do not hold. First, complementary relationships among ES abatement technologies provide additional opportunities for reducing abatement costs and increasing $w(t)$. For example, a group of corn growers in the same watershed or sub-watershed face obligations to reduce GHG emissions and nutrient runoff into the river. Growing more trees would reduce net GHG emissions, regardless of where they are grown, but would divert some land from corn. Growing more trees between cornfields and the riverbank would reduce nutrient runoff reaching the river but would divert some land from corn. (i) It is likely that planting trees along the riverbank would achieve both benefits at similar cost to the single-benefit alternatives, a clear net welfare gain. (ii) Not all of the farmers have land abutting the river but is likely that the group of farmers could negotiate an agreement to pay farmers along the riverbank to plant trees, at lower cost than individually addressing the GHG and nutrient runoff problems.

Second, the case of overlapping but non-coterminous problem sheds provides an additional complication. Suppose the units in a watershed emit pollutants damaging water and air quality, and that the air pollution impacts most of the watershed plus an additional area down-wind. Assuming independence of impacts and abatement technologies, water and air quality can be managed individually with little interactive impact, and there is no obvious benefit in coordination between water and air quality managers. However, there may be some complementarity and/or substitution among impacts and/or abatement technologies. In such cases, coordinated management would be beneficial, unless the costs of coordination outweigh the potential benefits.

3.2. Target Setting Using Sustainability Indicators, SI

Now we turn to the principles for target setting. We have identified a robust principle: where polluters are dispersed throughout the jurisdiction and damage is indifferent to receptors' location within the problem shed, abatement costs for any specific abatement target can be minimized by equalizing marginal abatement cost for all providers of a given ES in a specific problem shed. Larger scale tends to reduce cost of abatement and should be non-controversial where damage is indifferent to location within the problem shed. Policies aimed at cost-minimizing abatement of dispersed pollution may need to be augmented with specific provisions targeting large point-source polluters and local hotspots where ambient concentrations are unacceptably high. However, important questions remain: how much aggregate abatement should be sought, what marginal price of abatement should be set, and how can sustainability indicators and downscaled planetary boundaries help in target setting?

3.2.1. Sustainability Indicators

Sustainability indicators, SIs, have proliferated: Dasgupta et al. [9] recognize more than 240 SIs addressed to the sustainable development goals [10,11], and the most recent USEPA list [12] includes 83 SIs focused more narrowly on sustainability *per se*. SIs come in many different configurations. The primary divide is between those that hew closely to the concept of sustainability *per se* versus those based on the concept of sustainable development, which usually incorporates a broader base of concerns along the lines of wellbeing, the triple bottom line, etc. [31]. Here, I maintain a relatively narrow focus on SIs addressed to sustainability, as embodied (for example) in the USEPA's list of SIs [12].

SIs are numerical, but lists may include SIs using different measurement scales. Ordinal-scale SIs are useful only for ranking, e.g., we may ask whether a given jurisdiction is doing better or worse in terms of a particular indicator over time. These kinds of comparisons may be valuable to facilitate awareness, identify troubling trends, and motivate improvement, but they cannot be used effectively in fine-tuning abatement strategies.

Cardinal-scale SIs have order and distance, and can be useful for target setting, so long as there is agreement on a common baseline (the standard pedagogical example is temperature, where the freezing point of water at sea level serves as a common baseline for different scales). Better yet for target setting—setting trigger points for interventions and quantitative targets for improvement—ratio-scaled SIs have order, distance, and absolute zero. A quantitative target can be set for each s in jurisdiction k , and we can begin thinking about cost minimization, coordination among jurisdictions in a problem shed, optimizing over several kinds of s , and more.

The standard pollution policy framework posits structured relationships among three distinct phenomena: damage to human and natural systems, ambient pollution concentrations, and emissions. The goal is to reduce damage, which requires reducing ambient concentrations, and that can be accomplished by reducing emissions. SIs are intended to systematize the monitoring and tracking of empirical information useful in estimated science-based relationships among damage, ambient concentrations, and emissions. However, published lists of SIs can number in the hundreds [9,12] and tend to mingle (i) indicators of damage, concentrations, and emissions, and (ii) measurement scales. Given that SIs are commonly used at regional and local levels of governance, where policy makers and managers often are generalists, it is important to find coherent ways to winnow the long lists of SIs, retaining those most useful in identifying environmental threats familiar and emerging, monitoring trends, and targeting policy and management interventions.

Suppose that policy makers and managers are tasked to set limits on emissions in order to limit damage to human and natural systems. For the most part, damage is induced not by emissions *per se* but by the ambient conditions they create, for example, pollution concentrations in ambient air and water in lakes and streams. So, policy and management require information about three distinct phenomena: emissions, ambient conditions, and damage to human and natural systems. Ideally, these three phenomena can be measured and tracked with adequate accuracy and reliability, and science-based relationships between them have been estimated.

What SIs should we measure and track? We have already identified some criteria for winnowing long lists of SIs: focus on sustainability rather than sustainable development; use ratio-scale SIs whenever possible; track damage, ambient pollution concentrations, and emissions, but start with the kinds of damage to be reduced and prioritize SIs for those ambient pollutants and emissions that science has linked to the damage. Furthermore, there is variation among SIs regarding the level of aggregation. Emissions and ambient pollution often are cataloged by specific pollutants or categories of pollutants. Emissions can be tracked by source, which is useful if sources are regulated directly, if the regulator needs to know marginal abatement costs, and for monitoring trade in pollution reduction credits. SIs focused on damage tend naturally to be more inclusive than emissions indicators. For example, many different pollutants and combinations thereof can cause damage to human respiratory systems. Disaggregation often makes sense, but oversimplification can

undermine policy and management. SIs addressed to specific pollutants tend to simplify the tasks assigned to policy makers and managers, but over-simplification can lead to underachievement and higher costs when the complementarities, substitutabilities, and trade-offs that influence optimal policy are ignored. This issue has been recognized for many years [32]), but even modest progress toward resolution has come slowly [33–35].

3.2.2. Using SIs in Target Setting: Science and Values

Science-based SIs support science in mapping the possibilities, and are essential to rational target setting, but cannot alone determine the target levels. Human and social values must be invoked to settle questions such as how much damage is strictly unacceptable, and how great a cost should be borne to achieve better than merely acceptable levels of damage. While science aims at universality, science-based targets can be universal only if the values that determine the cut-off point are universal.

Should the same target apply across sectors, jurisdictions, problem sheds? As we have seen, abatement costs are likely to be reduced by setting ambient targets at the problem-shed level and facing all emitting units with the same marginal price of abatement. For a given set of values, lower abatement cost may lead to a somewhat higher abatement target, increasing $w(t)$ across the problem shed, especially in the case where damage is indifferent to location within the problem shed. However, this reasoning seems to be exhausted at the problem-shed level: where problem sheds are distinct, we cannot assume that values are identical, so different target levels may be chosen rationally even in cases where the findings of science are identical.

Even within a problem shed, the above discussion has assumed too readily that values are unanimous or nearly so. Especially when incomes and wealth are quite unequal, equity considerations may be an important driver of policy, if damage and/or abatement costs are dispersed unevenly in the problem shed. A hot spot with a disproportionate incidence of damage to human health is an important policy concern, as is a situation where abatement costs are borne quite unevenly.

3.2.3. Dashboards

Suppose a jurisdiction measures and tracks a set of SIs (existing examples range from relatively small numbers to more than one hundred members of the set). Each SI is measured on a scale—preferably, a ratio scale—monotonic in harm. For each SI, benchmarks are imposed—typically green, amber, and red—at pre-set levels, often representing broad consensus within and beyond the jurisdiction regarding the levels considered safe (green) and harmful (red). These benchmarks may be displayed on a dashboard, to facilitate communication and perhaps citizen involvement in decision making [36].

These benchmarks may be used: (i) within the jurisdiction, to identify and anticipate damage, set targets, help determine priorities among competing problems, inform decisions, monitor progress. (ii) Beyond the jurisdiction, within and beyond the problem shed, to facilitate benchmarking against other systems. However, given that the “safe” and “harmful” benchmarks are science-based, benchmarking against other systems is mostly for bragging rights: policy implications within the jurisdiction are triggered by red lights and perhaps foreshadowed by amber lights.

Do these uses of SI dashboards change any of the conclusions above? No: given benchmarks set on science-based SI ratio scales, the dashboard is an innovation in communication but does not change the fundamental character of the SI-based policy process. Given ratio-scaled indicators and science-based targets, the contribution of dashboards is mostly in assisting visualization in order to improve communication and perhaps engaging citizens in the policy discourse.

However, dashboards also serve to highlight some weaknesses that we have already identified in the SI framework. (i) An ideal dashboard would carefully distinguish among emissions, ambient concentrations, and damage. However, typical dashboards fail in this respect. (ii) Dashboards typically treat each SI as independent of the others, thus

encouraging their users to ignore the complementarities, substitutabilities, and trade-offs that influence optimal policy. One can imagine solutions to this problem but, again, progress has been slow [32–35].

3.3. Target Setting Using Downscaled Planetary Boundaries

3.3.1. Planetary Boundaries 1: Rockstrom et al. [21]

Rockstrom et al. proclaimed nine planetary boundaries, i.e., bright-line limits on resource exploitation backed with the claim that violating them dooms the planet. The PBs all address renewable resource systems—atmospheric carbon GHGs, freshwater systems, land systems, ecosystems, etc.—a sharp break with the earlier sustainability literature [23,24] worrying about exhaustible resources. To align the PBs with the standard categories of sustainability, define the PB as the outer boundary of the safe zone, SOS. Then, a safety criterion would call for a strong sustainability constraint at the global level to be invoked at the PB. For a given category of valued resources at time t , $SOS_t > 0$ if the total stock, $S_t > PB$. PBs are aligned also with the Precautionary Principle [37,38] which urges remaining inside the PBs to avoid the threat of intolerable harm. Barbier and Burgess [39] argue that the SOS can be treated as an exhaustible resource, but a forest provides a better metaphor: unless its growth rate and ecosystem services value justify maintaining a stock in excess of the PB, it may be optimal to deplete a forest, so long as global forests remain adequate. It seems also that weak sustainability is an appropriate criterion within the SOS, which is seen as a component of the inclusive wealth to be maintained to assure WS.

Note that the Rockstrom PBs place all the weight on the science piece of the science/values dichotomy. In the simplest formulation, collapse is certain beyond the PBs, and recovery from a PB violation is not a possibility: values are sidelined because global collapse is unthinkable in any plausible value system. However, there are plentiful threads of literature addressing both collapse and recovery as matters of chance [40,41], suggesting risk aversion rather than abandonment of all hope.

3.3.2. Planetary Boundaries 2, Steffen et al. [22]

The Steffen et al. amendments to the PBs formulation [22] address many of the concerns raised by the Rockstrom PBs, but at some cost to the uniqueness of the PBs idea. There is an amber (caution) zone between the green and red zones, and the zone boundaries are fuzzy, one zone shading into the next. The possibility of sudden regime shifts [42] is recognized explicitly. The outer boundary of the green SOS zone is still called the PB, but it shades into an amber zone of increasing risk which may include a threshold for regime change, and the amber zone shades into the red zone. The bright lines suggested by the notion of boundaries are gone. To address cases where we are already in the red zone, as with biogeochemical flows, Steffen et al. discuss prospects for creeping back across the threshold.

It can be argued that the “old wine in new bottles” metaphor applies to the Steffen et al. PBs. They are more nuanced and cover more of the possibilities than the Rockstrom original but seem to back-track toward the standard risk management framework, with zones of ordinary risk (as might be modeled by games of chance), increasing ambiguity and risk aversion, and the threat of sudden regime change. This framework implies a zone for ordinary risk management, a zone where precautionary risk avoidance might be recommended, and a zone in the middle where ambiguity and risk aversion are increasing [38]. Even the red zone has its own kind of ambiguity: it is to be avoided at all costs, but, if we are there already, we need to cobble together ways of creeping back across the threshold.

3.3.3. Are the PBs Truly Planetary?

The intuition for PBs can be defended most convincingly for global public goods. Several of the PBs are of this kind: genetic diversity, with a PB that already has been violated; carbon and climate, in the amber zone; ocean acidification and atmospheric ozone depletion, with some SOS intact; and atmospheric aerosol loading, with uncertain status.

In all of these cases, the problem shed is global and a PB is at global scale makes sense. The remaining PBs—freshwater use, land systems, ecosystem integrity, and biochemical flows—are not, or at least not entirely, planetary in that the problem sheds tend to be more localized and most of the rewards for management at the problem-shed level are enjoyed at that level. Many problems concerning freshwater and biogeochemical flows are manifested and best managed at the watershed level. Land systems to feed the world may be a global issue, but urban greenspace is much more a local concern. It can be argued that for problems that are manifested mostly at the problem-shed level, there is ample scope and motivation for variation across problem sheds in place-based objectives, approaches, and solutions.

So, my analysis continues with a focus on those PBs that are truly planetary, using atmospheric carbon GHGs as the paradigm case. Even in the case of global public goods, PB-based policy must be implemented by myriad decentralized units, economic sectors, and jurisdictions, which suggests the need for a credible method of assigning responsibility down at least to the jurisdictional level. Steffen et al. [22] insisted on the caveat that “the PB framework is not designed to be ‘downscaled’ or ‘disaggregated’ to smaller levels, such as nations or local communities” (p. 9). Regardless of this caveat, Steffen et al. saw potential uses of DPBs in helping coordinate local action with global imperatives, and other researchers have found the temptation to downscale the PBs irresistible.

3.3.4. Downscaled PBs

We are seeing the beginnings of a boom in downscaling the PBs to national, regional, and local scales [19,20,43,44]. “Think globally, act locally” is often cited as a motivation, and it has some plausibility: in the case of planetary public goods, action is typically place based, and local action is more readily comprehensible and hence easier to motivate; yet the problem has global dimensions that require coordinated action. Downscaled PBs for planetary resources can be used, with caveats elaborated below, to provide targets for local/regional action, and they appeal to notions not only of action, but (depending on the denominator) doing our fair share.

The downscaled PBs concept is both simple and flexible. For a PB, e.g., atmospheric carbon/GHGs, calculate DPB choosing an appropriate denominator (perhaps, but not necessarily, global population). Calculate DLF by calculating the local footprint—i.e. impact on the SOS associated with the particular PB—and dividing by, in this example, local population. That is,

$$\text{Compare DLF} = \frac{\text{local footprint}}{\text{local denominator}} \text{ with DPB} = \frac{PB}{\text{global denominator}}$$

The local ratio serves as an indicator for the locality, and $DLF \leq DPB$ or equivalently $DLF/DPB \leq 1$, can serve as a benchmark: a locality is doing at least its share if the local ratio is equal to or less than the global ratio. The simplicity is obvious: any hard empirical work lies in calculating the local footprint, which often involves the use of environmentally extended input-output analysis [45]. The flexibility is in the choice of denominator: a population denominator would imply that equity is a compelling value; \$GDP would imply a kind of efficiency, e.g., low carbon/GHGs per \$GDP suggests that production is relatively clean in that respect, but would also privilege wealthier countries; and contribution to accumulated ambient load would suggest grand-fathering historical emissions while its inverse would imply a kind of desert: a jurisdiction’s clean-up obligation is proportionate to its responsibility for the problem. In policy and management, the DLF/DPB ratio serves as an indicator benchmarked against the relevant PB. As such, it can serve as a motivator to raise awareness and help set objectives, a diagnostic tool that may reveal problems previously hidden and/or ignored, and to provide a sense of whether a given region or locality is part of the problem or part of the solution, and whether its performance is improving over time.

As argued above, PBs make most sense for global public goods. This conclusion is even clearer in the case of DPBs: carbon GHGs DPBs make sense because they directly address the question of whether a local jurisdiction is doing its share to solve a global problem; but DPBs for land tell us very little because, for example, urban greenspace matters, and is managed, mostly at the local scale. Yet, published DPBs typically take a set of local jurisdictions with some similarities (e.g., cities in the middle east and north Africa [43] and localities in the Yangtse valley [44]) and calculate DPBs for all nine PBs.

3.3.5. DPBs as Guides for Allocating Abatement and Conservation Effort

Suppose the goal is to identify efficient ways to conserve and sustain, win-win ways of incentivizing it, and fair ways of splitting the bill. We can identify some principles for using DPBs as guides for allocating abatement and conservation effort. First, for any DPB target addressed to a global public good, cost-minimizing abatement effort requires setting the marginal cost $c_{ijk} = \lambda$, $\forall i, j, k$ (Equation (4)). Given the likely dispersion of abatement costs among units and jurisdictions, it is likely that the λ incentive implies different proportional abatement targets for different units and jurisdictions relative to their baselines, with lower-cost abatement providers rewarded for making greater than proportional effort. Various combinations of payment for abatement effort activity and penalties for emissions can incentivize units to meet the $c_{ijk} = \lambda$ criterion. For a planetary public good, efficient payments and penalties are likely to imply transfers of income and wealth across jurisdictional borders. Mechanisms to set marginal abatement cost = λ include administered prices at the global level and trade based on DPBs. For trade, all jurisdictions would be capped at their DPBs, and each jurisdiction with a footprint less than its DPB would receive pollution reduction credits equal to the difference and could earn additional credits by further reductions in footprint. Jurisdictions with footprints greater than their DPBs would need to abate or purchase credits to balance their DPB accounts. Subsequent global trade in credits would establish λ . Note that DPB-based cap-and-trade would take place at the jurisdictional level, leaving jurisdictions to transmit the incentives down to the unit level. If global coordination is too much to ask, a coordinated subset of jurisdictions could trade credits to meet its group DPB responsibility.

Second, by choice of denominator, DPBs can be used to highlight particular concepts of fairness and empower them in policy and management. In the case of atmospheric carbon GHGs, a DPB per capita implicitly assigns equal abatement responsibility per capita, whereas a denominator based on the inverse of contribution to accumulated carbon GHGs would direct responsibility toward those countries that have contributed most to the current global climate problem.

Third, given global inequalities, different jurisdictions will have different baseline incomes and wealth and different capacities to bear abatement costs. Pragmatic concerns (e.g., motivating abatement effort) and considerations of fairness (e.g., reducing or at least not exacerbating inequalities) are likely to work in similar directions, suggesting inter-jurisdictional trades that tend in the net to encourage and reward relatively low-cost abatement effort. To the extent that lower abatement cost regions are located in low- and middle-income countries, the flow of payments would tend to reduce existing inequality.

3.3.6. Do Downscaled PBs Have Advantages over Other Science-Based Targets?

PBs are not without their critics [46], but I argue that they make sense for truly global public goods. Among the nine PBs, atmospheric carbon GHGs, aerosols, and ocean acidification are the cleanest cases. Where problem sheds are smaller than the planet, problem-shed scale solutions are more suitable. This leads to a much smaller set of DPBs than PBs, and a very much smaller set than SIs, which can number in the hundreds.

The PBs are much more focused on sustainability per se than the SIs, which may well include a broad range of wellbeing indicators. Depending on one's perspective, the laser focus on sustainability as opposed to the broader SDGs may be considered an advantage or a disadvantage [31,36].

Whereas SIs include those measuring emissions, ambient concentrations, and damage to human and natural systems, DPBs tend to focus on ambient conditions. The connection to emissions, the targets for policy and management, must be established by science.

Whereas science-based SIs require values to set targets, the Rockstrom et al. PBs take values out of the calculation by insisting that violation of the PB dooms the planet, a fate that any value system would deplore. However, it must be noted that there is fuzziness regarding planetary boundaries since Steffen et al. [22] tends to vitiate this advantage.

In any event, the processes of downscaling and target setting at the jurisdictional and unit levels have the potential to reintroduce values, perhaps inadvertently as might be the case where cost minimization is a prime consideration. DPBs also offer opportunities for purposeful introduction of specific values in the choice of denominator. Policy design may draw upon both of the above processes. For example, a cost-efficiency framework might be bounded by side constraints: perhaps a strong preference for incentive payments that flow from richer to poorer countries, and relief from efficiency criteria in the case of serious threats to human health and nutrition.

3.4. Target Setting with Cost–Benefit Criteria

3.4.1. The Cost–Benefit Criterion

Assuming dispersed polluters and damage indifferent to location within the problem shed, we readily can characterize efficient abatement policies, i.e., those that maximize net social benefits. Suppose we can estimate the social benefit of abatement, $B_s(e_s)$; there is a large literature, which I will not explore here, on methods of so doing. We also need information on abatement costs, which may be estimated using engineering-economic methods, approached by regulators iteratively adjusting their price incentives to hone-in on an abatement target, or discovered in cap-and-trade markets. Then we can maximize the contemporaneous net benefit (i.e., benefit minus cost) of abatement problem shed wide at time t :

$$\text{Maximize } (B_s(e_s) - \sum C_{sijk}(e_{sijk})) + \lambda(\sum e_{sijk} - e_s) \quad (5)$$

First-order condition: $c_{sijk} = b_{sk} = \lambda, \forall i, j, k$.

The target level of abatement, e_s^* is endogenous, i.e., the level at which marginal social benefit = marginal cost = λ , and can be achieved by facing all units with the same marginal price of emissions λ . All else equal, w_t increases with the net benefit from abatement, and is maximized when $b_{skt} = c(e_{sijkt}) = \lambda$ for all i, j , and k globally. The target level of abatement is optimized, and all polluters are faced with the same marginal price of emissions—whether transmitted by administered prices or trade in pollution reduction credits—which minimizes the cost of attaining it. As has been caveated, such policies might serve as the regulatory default, although they may need to be augmented with specific provisions targeting large point-source polluters and local hot spots where ambient pollutant concentrations are unacceptably high. If we sustain optimal abatement through time, all else optimal, $w^*(t)$, the highest feasible level of weak sustainability, will be attained.

Equation (5) seems to suggest that a single ES, s , is to be evaluated, and that is often the case. However, s could be a coherent suite of ESs without changing the main conclusions. To elaborate, it may be possible to identify a group of ESs that are substitutable and/or complementary, package them in ways that take advantage of these interrelationships, and then find the size of the package that maximizes net benefit. The result will be different to, and its contribution to $w(t)$ greater than, that obtained with piecemeal policies optimizing the same ESs individually without regard to substitutability and complementarity.

The CB approach has considerable advantages. It provides a rigorous and transparent framework for targeting abatement efforts, using information in the form of science-based estimates of the relevant production possibilities, and willingness to pay as a measure of preferences [47]. It provides a framework for evaluating one-dimensional policies and multipart policy packages whose components may exhibit substitutabilities and complementarities, and it is sensitive to trade-offs among candidate abatement activities. It can play an important role in models designed to allocate abatement effort across many po-

tential projects to maximize social net benefits. To the extent that SIs and/or DPBs are selected and organized to facilitate the assessment of costs and/or benefits, the SI and DPB approaches can be incorporated in a cost–benefit framework.

3.4.2. The Concept of Social Benefits

While the general idea of social benefit is broadly understood, its implementation by economists depends on some quite specialized assumptions that are not so widely accepted. The CB framework is responsive to human preferences, which motivates objections from a variety of ethicists including those more comfortable with arguing from rights or duties, those who value the intrinsic worth of nature, and those more inclined to place humans within the ecosystem rather than above it [47]. In the absence of gross inequality, utilitarian objections to the benefit cost criterion are relatively few and typically hinge on claims that people don't really know what is good for themselves. However, the value measures—willingness to pay for gains in ES and to accept compensation for losses—are sensitive to differences in income and wealth such that the preferences of the better-off count for more [47]. This concern is more urgent when substantial inequality is the norm, and currently inequality is troublingly large at the national level, and pervasive at the global level. The equity concerns thus introduced suggest need for some restraints on the influence of cost and benefit considerations.

3.4.3. Costs, Benefits, and Weak Sustainability

The cost–benefit, CB, approach and weak sustainability share the same concept of contemporaneous welfare [1,48–50]. Nevertheless, CB and WS may differ about what constitutes appropriate provision for the future. WS insists that sustainable welfare means equal welfare for each succeeding generation [41]. The CB approach maximizes the net present value, NPV, of the $w(t)$ stream and in so doing may tolerate two kinds of deviations from intergenerational equality: positive time preference, which systematically favors earlier generations; and variability in $w(t)$ over time such that some generations might enjoy more welfare than others, so long as NPV is maximized. Regarding variability in $w(t)$ over time, it can be argued that planned variability is inconsistent with WS and, in the event of unplanned variation, the intergenerational commitment to pass non-diminishing IW to successor generations might be interpreted with an “on average” caveat that grants unlucky generations a little relief from the saving commitment under WS but expects lucky generations to make up the slack [41]. Regarding the time preference issue, Asheim has offered a resolution [51,52]: intergenerational equality requires that discounting be limited to the expected growth rate of future welfare, which implies zero discounting for time preference.

3.4.4. Using CB Criteria and SIs to Set Targets

Environmental policy makers and managers cannot manage $w(t)$ directly. Instead, they try to manage e_s in order to achieve e_s^* , in the context of managing the whole economy for the benefit of society. In consequence, they need credible indicators of e_s , ambient s , and damage to human and natural systems. The CB approach is science based in the same way as the SIs approach—requiring reliable science-based measures of, and empirical relationships among, emissions, ambient concentrations, and damage to map the possibilities and trade-offs—but imposes a particular preference-based notion of values. The CB approach is inherently project and program oriented, and projects and programs can be structured to provide coherent packages of enhancements to multiple ESs, thus supporting a broader menu of policy analyses valuing, for example: enhancement of s in the context of other ES, accounting for any substitutability and complementarity relationships; enhancement of s in multi-component policies, accounting for any substitutability and complementarity relationships among the components; enhancement of environmental policy packages that include s in the context of competing priorities; and enhancement of s , or policy packages that include s , in the context of comprehensive welfare maximization.

Substantial empirical work is required to implement these various analyses, especially the more comprehensive kinds, but the CB approach provides a coherent framework for so doing.

The CB framework does not substitute for SIs. Indicators are essential for measurement and monitoring of ES, but the need is for fewer and better indicators, indicators more attuned to beneficial results and opportunity costs, and for indicators that address the complementarities and substitutabilities that occur in the real world. The BC framework provides a structure for addressing these needs.

3.4.5. Can CB Criteria and DPBs Be Used Together to Set Targets?

For global public goods, DPBs cut through the proliferation of SIs and focus on ambient conditions that relate directly to damage to human and natural systems. They may be used to allocate abatement responsibility to localities and regions, often guided by an explicit equity criterion. Unfortunately, issues of substitution, complementarity, and multi-component policies tend to be submerged in the PBs discourse. Nevertheless, minimizing the cost of remaining within the PB remains a valid concern, and methods of accomplishing it are discussed in Section 3.3.5. The role of benefits is less prominent, because given a credible PB for a global public good, remaining within that PB is not a choice but an imperative.

3.4.6. Equity Implications of CB Approaches

Inequality is troublingly large at the national level, and pervasive at the global level. Yet the standard measures of benefits and costs are sensitive to differences in income and wealth, raising equity concerns. By way of example, consider two cases at global scale. First, human health is mostly a private good and its provision in lower-income countries is mainly a matter of equity. Transfers from well-off countries to subsidize human health in lower-income countries likely reflect two quite different motivations: a compassionate desire to reduce human suffering in low-income countries, and a self-interested fear of contagion which provides an incentive for wealthy countries to support global health. To the extent that CB analysis is applied to international efforts in global health, benefit estimates are much impacted by ability to pay and, when inequality is severe, the preferences of well-off societies will garner more attention. In such cases, we must anticipate calls to replace demand-based measures of benefit with measures more sensitive to human needs.

Second, atmospheric GHGs are pure public goods in that emissions anywhere are equally damaging. In such cases, equity and pragmatic considerations tend to work together, such that cost-minimizing abatement of carbon GHG emissions is likely to involve inter-regional and international subsidization of abatement in places where incomes and/or abatement costs are lower, a practice that is likely to reduce but not eliminate the inequities [53].

4. Further Research

Given the broad sweep of this article, there is a temptation to argue that more research is needed on almost every facet mentioned or implied in this article: sustainability concepts; modeling of complex human and natural systems; measurement and modeling of relationships among emissions, ambient conditions, and damage; design and implementation of SIs and DPBs; design of incentives to reveal abatement costs and encourage compliance with abatement commitments; theory and application of CB analysis; and measurement of costs and benefits. It is more constructive, I think, to highlight a few high-priority research areas.

The proliferation of SIs is both a triumph and indictment of contemporary science. We can measure and monitor many more indicators related in some way to sustainability and/or sustainable development. However, we need much more research to winnow the existing SIs, identifying those most directly related to design of more effective and efficient

policy and management interventions. Then, the surviving SIs need to be restructured, muffling the unintended invitation to piecemeal policy and advancing the goal of coherent policy packages taking full advantage of the substitutability and complementarity relationships among policy components. This may be an area where the elusive goal of true convergence can be attained.

The evolution of the PBs research program from the bright-line boundaries [21] to a framing [22] that is both more nuanced and more like the mainstream concept of risk [38] suggests a need for yet more research to establish whether PBs become central to the sustainability discourse or just another tool in a broader toolkit.

While transactions costs are caveated here, and it is assumed that coordination can be attained relatively easily, there is so much more to be said, and learned, about these issues. In the relatively simple case of a naturally bounded problem shed, the starting point really matters: coordination is easier and transactions cost lower if a problem shed-wide coordinating body already exists and has real authority. Whether a problem-shed level body should devolve some of its authority to local jurisdictions is resolved more easily, I hypothesize, than whether a group of empowered local jurisdictions should cede authority to a problem shed-wide body. We would expect global coordination addressing carbon and climate to be much more difficult, and that has turned out to be the case, but the search for effective ways to break the impasse remains urgent and involves issues of governance and coordination as well as science and engineering.

5. Conclusions

The foregoing analyses and conclusions apply, in some cases with modest amendments, to enhancements of environmental services, s , achieved by pollution abatement or resource conservation. The example of pollution control has been used throughout. Define scale as increasing in (i) households, plants or firms i in a sector, (ii) the number of sectors j , and (iii) the number of jurisdictions k , and assume that increasing scale increases the dispersion of abatement costs, $C_{ijk}(e)$ for a given level of emissions, e . The findings summarized below apply to the default case where polluters are dispersed, and damage is indifferent to location within the problem shed. Policies aimed at cost-minimizing abatement of dispersed pollution may need to be augmented with specific provisions targeting large point-source polluters and local hotspots where ambient concentrations are unacceptably high.

Regardless of the targeting strategy and the level of target chosen, cost-minimizing achievement of target emissions e' requires a pollution abatement incentive λ at the margin for all units in a given jurisdiction. In the likely case that dispersion of abatement costs is increased by extending the geographic scope of regulation to the entire problem shed, total abatement costs can be reduced by combining, or coordinating, all jurisdictions in the problem shed.

Targeting environmental improvements requires two kinds of information: science-based measurement and estimation of relationships among emissions, ambient conditions, and damage to human and natural systems; and values to prioritize among the many ES that contest for attention as we seek sustainability.

Targeting using sustainability indicators, SIs, allows for cost minimization in attaining an aggregate e' target. However, the proliferation of SIs that vary in focus (sustainability per se or sustainable development), scale and scope (a single pollutant, or a health syndrome caused or exacerbated by many different pollutants), kind (emissions, ambient concentrations, or damage), and measurement scale (ordinal, cardinal, or ratio) calls for a purposeful winnowing to identify those most useful in identifying environmental threats, monitoring trends, and targeting policy and management interventions.

There remains a concern that SIs encourage piecemeal policy, seldom accounting for potential gains from complementarities and substitutabilities among ES.

Targeting using downscaled planetary boundaries, DPBs, is feasible and *prima facie* sensible for global public goods. Given that meeting the PB is framed as imperative, there

is little place for CB analysis to provide benefit estimates for setting abatement targets. Nevertheless, cost minimization remains a relevant goal, and can be motivated by a global administered price or global trade in pollution reduction credits. If global coordination is too much to ask, smaller groups of willing nations can calculate their collective DPB and achieve it cost effectively via administrative prices or trade in credits.

CB optimization for enhancing a particular s requires that $c_{sijk} = b_{sk} = \lambda_s$, $\forall i, j, k$ in the problem shed (Equation (5)), and the target level of abatement, e_s^* , is determined endogenously. The CB framework can be used to optimize a set of abatement initiatives, and to optimize environmental policies in the context of competing priorities, but these tasks can demand a lot from the theory, data, and analysis. If formal optimization is too much to ask, approximately optimal packages of environmental initiatives are likely to increase welfare, perhaps dramatically relative to a world in which each locality enhances each of its SIs one by one.

The standard measures of benefits and costs are sensitive to differences in income and wealth, raising equity concerns. First, the standard measures of costs and benefits are influenced by ability to pay so that the preferences of better-off people and societies garner more attention. This suggests that, even in well-off countries, a case can be made for relieving health and nutrition programs for the poor from CB filters. Second, international inequalities in income and wealth being even greater, transfers from well-off countries to subsidize human health in lower-income countries likely reflect not only a compassionate desire to reduce human suffering in low-income countries, but also a self-interested fear of contagion which provides an incentive for wealthy countries to support global health. Similarly, for global public goods such as abatement of carbon GHG emissions, cost-minimizing abatement is likely to involve inter-regional and international subsidization of abatement in places where incomes and/or abatement costs are lower, a practice that is likely to reduce but not eliminate the inequities [53].

Finally, I note that PBs are compatible with strong sustainability and the precautionary principle. The welfare foundations of the CB framework are consistent with weak sustainability in a single time period but may depart from WS over time unless constrained by a requirement of non-diminishing $w(t)$ through the generations. The diversity of SIs precludes general statements about their relationship to the standard sustainability concepts.

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