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Research Report

Sustained timber yield claims, considerations, and tradeoffs for selectively logged forests

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ABSTRACT

What is meant by sustainability depends on what is sustained and at what level. Sustainable forest management, for example, requires maintenance of a variety of values not the least of which is sustained timber yields (STYs). For the 1 Bha of the world's forests subjected to selective or partial logging, failure to maintain yields can be hidden by regulatory requirements and questionable auditing practices such as increasing the number of commercial species with each harvest, reducing the minimum size at which trees can be harvested and accepting logs of lower quality. For assertions of STY to be credible, clarity is needed about all these issues, as well as about the associated ecological and economic tradeoffs. Lack of clarity about sustainability heightens risks of unsubstantiated claims and unseen losses. STY is possible but often requires cutting cycles that are longer and logging intensities that are lower than prescribed by law, as well as effective use of low-impact logging practices and application of silvicultural treatments to promote timber stock recovery. These departures from business-as-usual practices will lower profit margins but generally benefit biodiversity and ecosystem services.

Keywords: forest management, natural climate solutions, nature based solutions, climate change mitigation, timber growth and yield

Significance Statement:

Commitments to sustainable forest management (SFM) deserve praise, but also scrutiny. Here, we examine the sustained timber yield (STY) component of SFM for the 25% of Earth's forest subjected to selective logging. Legitimacy of STY claims depend on whether, over time, the number of species included in yield calculations increases, minimum cutting diameters decrease, or lower quality logs are accepted. STY is possible without such dubious accounting practices if harvest intensities and collateral damage decrease, harvest intervals increase, and treatments are applied to promote recovery. These changes will reduce profits relative to those of timber mining, but climate-change mitigation funds should be available to cover some of the costs given the carbon and other benefits of responsible forest management.

Introduction

The concept of sustainability, first applied to timber by foresters in the 17th Century (1), was later expanded to include consideration of nontimber values as embodied in the phrase sustainable forest management (SFM). It broadened further after publication of "Our Common Future" (2) and codification in the Sustainable Development Goals of the United Nations (3). Unfortunately, the term sustainability is often now applied so widely that it lost much of its meaning (4), as illustrated by the oxymoronic Journal of Sustainable Mining. Here, we return to yield sustainability as a core requirement for sustainable management of renewable natural resources with a focus on sustained timber yield (STY) from selectively or partially logged forests. This narrow focus is justified by the estimated 1 billion ha of forests subjected to this sort of logging (Supplementary Materials). Despite being an anathema to some environmentalists, many of these forests will continue to be logged for many reasons including increased global demand for timber (5). It also needs to be considered that sound forest management can contribute to achievement of economic development goals (6), is orders-of-magnitude more biodiversity-friendly than forest conversion (7), and provides opportunities for climate change mitigation (8). Precise definitions of STY are needed to

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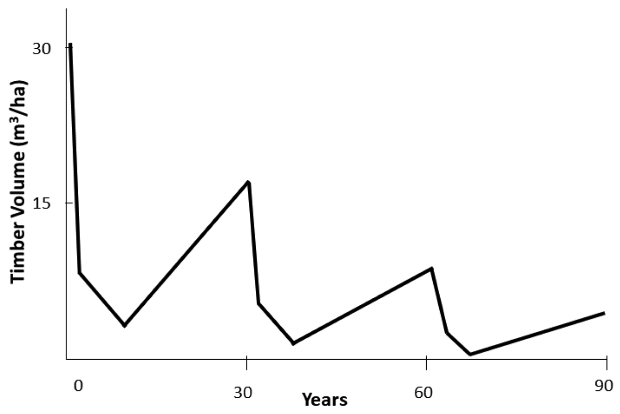

Fig. 1. Standing volumes of timber from natural forests subjected to selective harvests of trees greater than some MCD at 30-y intervals. On the Y-axis, which shows standing timber volumes, 30 m^3 ha^{-1} is used as the maximum only for illustrative purposes.

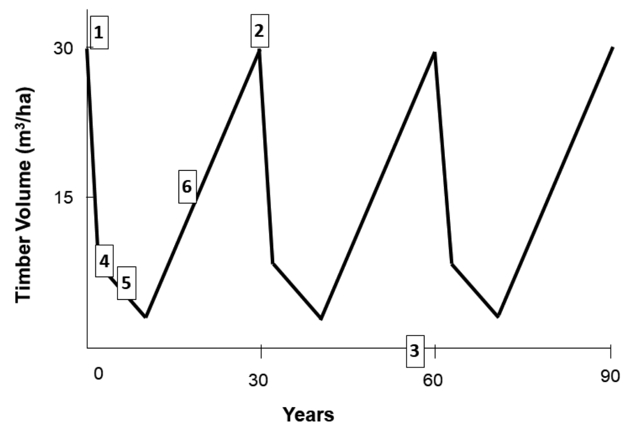

Fig. 2. Theoretical but seldom realized STY; the numbers refer to variables explored in the text and illustrated in subsequent figures. #1 pertains to the many different variables that can be plotted on the Y-axis. #2 represents the volume at which yields are to be sustained. #3 represents variations in cutting cycle duration. #4 concerns harvest intensity. #5 shows temporary increases in tree mortality after a selective harvest, as influenced by logging intensity and use of reduced-impact logging practices. #6 refers to the speed of timber volume recovery, as influenced by logging practices and silvicultural treatments.

inform decisions about the three pillars of sustainability: environmental protection; economic development; and social welfare (9).

By focusing on the biophysical aspects of forest management for timber, we disregard but do not diminish the importance of issues related to forest ownership and management responsibilities. We also only consider biodiversity and ecosystem services as tradeoffs or synergies associated with achievement of STY. We believe that successful promotion of sustainability requires clarity about whether management objectives are achieved, as indicated by comparison with specified reference conditions.

Emphasis on selective logging requires clarification. In mixed-species forests, timber harvests are typically partial because not all species produce merchantable timber; the exception is where mixed forests are clearcut in the process of converting them to even-aged stands (10). Outside of experimental plots and strictly regulated public forests, selective harvests are often controlled only by government establishment of minimum cutting diameters (MCDs) below which trees cannot be harvested legally and minimum cutting cycles designed to preclude premature re-entry logging.

Defining STY by its absence

One way to define STY is to clarify its absence. Here and in the following diagrams, the same basic model is used in which time is plotted on the X-axis and some measure of standing stocks of timber is plotted on the Y-axis (Fig. 1). The steeply declining lines show the immediate effects of harvests on standing timber volumes; included are logs extracted from the forest, wood wasted, trees felled but then abandoned on the forest floor, and trees that suffer fatal collateral damage. Selective harvest cycles of 30 y are portrayed not because many forests recover their preharvest timber volumes in that time period but to reflect the average minima set by governments (10 to 60 y). The subsequent less steeply declining sections of the curves reflect the continued loss of timber volume due to elevated rates of post-logging mortality from stand damage and changes in environmental conditions. After declining, volumes of commercial timber recover at rates that reflect stand conditions, particularly the residual stocking of trees and post-logging weed proliferation.

Fig. 1 depicts the fates of many selectively logged forests such as those in Africa (11), South America (12), Southeast Asia (13), and private nonindustrial temperate forests in eastern North America (14) and Europe (15). The illustrated forest is clearly not maintaining timber yields and is thus not being managed sustainably. We need to acknowledge, however, that if a "weak" definition of sustainability is applied that allows transfers among the five capitals (i.e. natural, built, social, financial, and human), Fig. 1 need not represent unsustainability (16). But even "strong" sustainability (i.e. all capitals are maintained) requires a clear definition of "critical" natural capital that reflect socio-environmental and other values (17). Here, we focus on timber producing forests and consider declining yields as the antithesis of STY.

What is sustained?

The effects of partial timber harvests on forest conditions can be represented by many different Y-axis variables (Fig. 2, Point #1). These variables can refer to small and homogeneous areas of forest subjected to the same treatment (i.e. stands) or to entire forests. Other options include representing the volume of all trees larger than the minimum censused diameter (typically 10 or 20 cm stem diameter at 1.3 m) or trees larger than government-mandated MCDs. We note that if the model of sustainable fisheries is followed (9), then tree size would be allowed to diminish as long as the overall volume of timber does not. The Y-axis measure could also refer to timber volumes in all trees or only well-formed trees of commercial species; if the latter, which list of species is used matters considerably given that these lists tend to grow over time (18,19). Finally, the Y-axis could pertain only to commercial trees larger than their legally established MCD with boles of commercial quality.

Some options for representing timber yields that seem like attempts at obfuscation and violate the accounting principles of consistency and comparability are perhaps justified by changes over time in governmental regulations, marketing opportunities, timber availability, and processing technologies. For example, while the efficiency of conversion of logs into lumber increases with log size, scarcity of large logs of prime quality motivates acceptance of smaller and defective ones. In this case, technological advances in wood processing can increase conversion efficiencies. It would also be reasonable for managers to represent the volumes of all trees of all species if wood not suitable for lumber or veneer can be converted into marketable products (e.g. chip board, oriented strand board, cross-laminated, and glulam lumber) or used for fuel (20).

Shifting species with each harvest, referred to as "logging down the value chain" (18,19), is commercially justified because, over time, "lesser known" species often gain market acceptance. Such changes also occur where preferred species become unavailable due to previous over-harvests, climate change, and/or introductions of exotic pests and pathogens [e.g. chestnut blight and others in the deciduous forests of eastern North America (20)]. Temporal shifts in harvested species can also reflect regeneration or growth failures of commercially valuable species such as of *Tabebuia impetiginosa* (ipê) in Brazil (20) or *Betula alleghaniensis* (yellow birch) in Michigan, USA (21). Either way, if growth and yield portrayals are to be understood, then the length and composition of the list of commercial species deserves critical scrutiny. The shortest list is of currently marketed species; the longest list includes all species ever marketed anywhere.

Sustained at what level?

Fundamental to considerations of STY is the level at which yields are sustained (Fig. 2, Point #2). For forests commercially logged for the first time, a paradox emerges if preharvest stand conditions are used as the reference state. One consideration is whether the abundance of some species reflects unrecorded and sometimes subtle historical human interventions (22). Changed conditions are suspected where commercial species do not successfully regenerate without creation of conditions markedly different than those occurring immediately preharvest (23, 24). Furthermore, actively managed areas may intentionally differ in structure and composition from old-growth forest (e.g. increased stocking of future crop trees); deeming this forest degradation (25) denies the capacity for responsibly managed forests to deliver many benefits society desires but with tradeoffs that need to be clarified.

Where timber accumulated over hundreds of years prior to the first industrial harvest, it seems unreasonable to expect a logged forest to recover this volume within economically viable cutting cycles of 30, 60, or even 90 y. If we come to terms with this limitation, STY might justifiably refer to some lesser volume at which yields are sustained in perpetuity. In the US Pacific Northwest, for example, the intention is to sustain yields at 50% the volume of the first modern industrial commercial harvest; this difference is referred to as the "primary forest premium" (26), with "premium" referring to both timber volumes and profits and "primary" equated with forest with no signs of recent human incursions (Point #2 on Fig. 2, dashed line on Fig. 3). Choices of primary forest premiums should be informed by empirical evidence about the tradeoffs but are essentially normative in nature.

If primary forest premiums are accepted, at what level should they be set and by whom? Unfortunately, the few precedents seem to maximize short-term financial profits at the expense of long-term social and environmental benefits. What is clear is that stands managed to sustain timber yields at 80% of the first cut will differ from those where the goal is only 50%. Whatever level is chosen, clarity is critical lest claims of STY be misconstrued.

The expectation that managed forests will recover primary forest conditions disregards the fact that they continue to be logged, irrespective of whether any of the world's remaining primary forests should be harvested. This politically charged issue, which looms large in some countries [e.g. Canada (27); Australia (28); Democratic Republic of Congo, Brazil, and Indonesia (29)], usually pits local, regional, or national prosperity against other values.

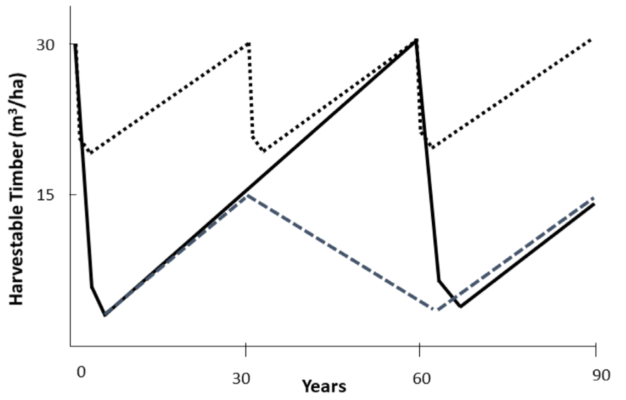

Fig. 3. Timber yields sustained by lengthening cutting cycles (solid line), reducing harvest intensity (dotted line), or accepting a primary forest premium of 50% (dashed line).

Where little primary forest remains in a region, which is the case in most temperate and an increasingly large portion of tropical forests (30), reference state selection is less clear. Perhaps the most appropriate comparator would be stands immediately prior to their harvest, unless other societal preferences are known. Whatever the choice of reference conditions, the decision is complicated by the aforementioned direct and indirect effects of previous management practices and climate change coupled with introductions of exotic pests, pathogens, and weeds.

Harvest frequency

A frequently recommended but seldom adopted way to achieve STY is to lengthen cutting cycles (Point #3 on Fig. 2 and solid line on Fig. 3). For example, Sist *et al.* (12) recommended that selective harvests from Amazonian forests should be restricted to 10 m^3 ha^{-1} at 60-y intervals, which is far less than current legal harvests of 20 m^3 ha^{-1} at 35-y intervals. Even with the currently abbreviated harvest cycles, second cuts are often not profitable (13, 31).

When cutting cycle prolongation is recommended and the total harvested area is not increased, short-term profits to loggers and forest owners decrease, which compels forest industries to find alternative sources of logs, a type of activity-shifting leakage (i.e. displaced loggers harvest timber elsewhere). If log supplies are allowed to diminish, forest industries will be forced to down-size, which will reduce both employment and revenues to forest owners. For these reasons, policy changes that reduce timber supplies are challenging to implement without compensatory payments for carbon sequestration or other forest benefits (32).

Increasing the area of forest exploited to compensate for volumes foregone by reduced harvest intensity will justifiably be objected to by environmentalists, especially given the additional roads that facilitate access by wildlife poachers, illegal loggers, land-grabbers, and other undesirables (33). Environmentalists dedicated to maintaining what remains of the world's intact forest would obviously object to expansions of forestry footprints (34). Moreover, given that logging is among the world's most dangerous professions (35) and that risks to workers increase with remoteness of operations, social welfare concerns should loom large when expansion of harvest areas is considered. One small advantage to controlled extensification is the relative ease of detection of logging roads from satellites (36); detection of illegality is a prerequisite for law enforcement.

Government-mandated minimum cutting cycles become difficult to enforce over time; even without changes in operational

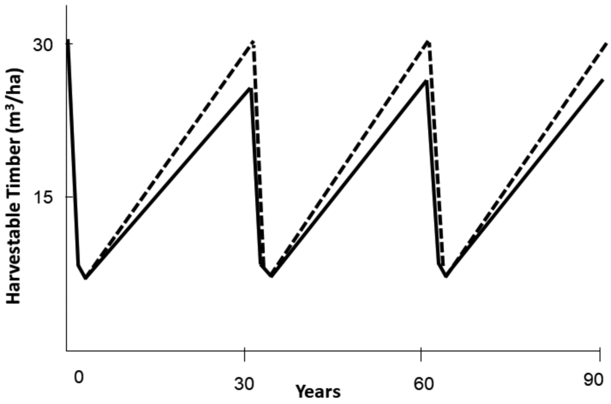

Fig. 4. Timber recovery after RIL (solid line) or RIL followed by application of silvicultural treatments that enhance stand recovery rates (dashed line).

planning staff, cutting block boundaries are often redrawn at decadal intervals in the process of management plan revision. The often recommended regulatory intervention of lengthened cutting cycles (37) is further complicated in Indonesia where minimum cutting cycles are used to calculate the proportion of a forest that can be harvested annually, but where these harvests occur is left to the discretion of forest managers (38).

Reduce harvest intensity

Standing stocks of timber recover more quickly if less is harvested [Point # 4 on Fig. 2 and dotted line on Fig. 3; (39)]. Regulations designed to reduce logging intensities typically increase MCDs, set maximum cutting diameters, require a minimum residual stocking or a minimum distance between felled trees, and/or restrict harvests by species. Preventing premature re-entry logging, either legal or illegal, is obviously required for this management approach to deliver the expected future yields.

Restrictions on harvest intensities increase long-term timber yields, but reduce short-term profits and suffer the same conservation and financial constraints as lengthened cutting cycles. Moreover, low intensity single-tree selection systems do not provide the large canopy gaps required for the regeneration of light demanding species [e.g. *Swietenia macrophylla* in tropical America (40), *Terminalia superba* in tropical Africa (22), and *Betula alleghaniensis* in temperate North America (41)].

Improve harvest quality

Use of reduced-impact logging practices (RIL; Point #5 on Fig. 2 and solid line on Fig. 4) can lessen stand damage while maintaining harvested volumes (42). RIL adoption can lead to demonstrable carbon emissions reductions that can be accounted with the “Reduced-Impact Logging for Climate Change Mitigation” (RIL-C) protocol (43). Also important is that after RIL, forests typically recover their carbon and timber stocks more rapidly than after conventional logging (44).

In addition to reduced collateral stand damage and the retention of more intact future crop trees, directional felling to preplanned skid trails reduces the area of soil damaged by the heavy equipment used to drag logs to collection points, which keeps more of the forest productive; root growth is impeded in compacted soils and bulk density recovery can require decades (45). Another benefit is that lianas, shrubs, giant herbs, and other disturbance-adapted weeds are unlikely to proliferate in the small canopy gaps that result from RIL. Finally, with detailed harvest plans implemented by trained workers, fewer felled trees are carelessly left in the forest, more timber is recovered from harvested trees due to reduced log breakage and wastage, and there is less collateral forest damage (46).

RIL alone does not guarantee that commercial timber yields will be sustained, at least not with currently government-mandated MCDs (12, 13, 37). One already mentioned problem is that small canopy gaps do not favor regeneration of light-demanding commercial timber species. Another problem is that the benefits of RIL are diminished at logging intensities of >8–10 trees ha^{-1} or >40 m^3 ha^{-1} (37). Finally, on steep slopes and in deep swamps where forest management is increasingly relegated due to conversion of forests on more suitable terrain, successful RIL may require switching from dragging logs out of the forest with bulldozers or skidders, which causes substantial soil and collateral forest damage, to extracting logs from the forest with long cables so that heavy machines traverse little of the harvested area (47).

Apply silvicultural treatments

When RIL is combined with appropriate silvicultural treatments (Point #6 on Fig. 2 and the dashed line on Fig. 4), rates of post-logging commercial timber volume recovery can increase, which allows STY with shorter cutting cycles. For example, liberating the crowns of future crop trees from the effects of nearby and overtopping competitors can substantially accelerate timber volume increments (14, 48).

Silvicultural treatments, like any other intervention, entail tradeoffs insofar as management for something (e.g. timber) requires management against something else. For example, where lianas are abundant, cutting them is a cost-effective way to promote tree growth (49), but lianas produce foliage, flowers, and fruits consumed by wildlife while they provide inter-crown pathways for nonvolant canopy animals (50). The most intense silvicultural treatment prescribed for natural forests managed for timber is enrichment planting of native species along cleared lines through logged-over or secondary forest, which can greatly increase stocking of timber but can render treated stands plantation-like (48). Finally, where tree planting and other silvicultural interventions are successful, additional controls on harvesting beyond setting a MCD will be needed to avoid stand devastation when the heavily stocked stands are logged (13).

Interdependencies and Limitations

The STY variables previously presented individually often vary simultaneously. For example, as timber stocks available to forest processing industries decline, smaller logs of lower quality of more species tend to be accepted. In Costa Rica, for example, trees more than 30 cm in diameter of almost any species are harvested legally (51). The critical point here is that other than where yields are sustained from the same species with logs of the same size and quality, claims of STY deserve scrutiny.

STY as a component of sustainable forest management should be evaluated at a range of spatial scales up to landscapes (52–54). For example, large areas allocated for timber management could be stratified by land-use capability and associated operational costs. Intensive silvicultural interventions, such as enrichment planting, would logically be allocated to accessible areas on gentle terrain. In more remote areas with higher operating costs and lower profit margins, low logging intensities or no logging at all are more appropriate. At the jurisdictional level at which concerns about maintaining timber supplies loom large, restoration of degraded lands and even limited conversion of forests into plantations might be accepted as elements of overall landscape management strategies.

Securing STY almost invariably reduces short-term financial gains. Profits, or at least timber yields, can be sustained indefinitely but at reduced levels if cutting cycles are extended, logging intensities are reduced, logging practices are improved, and silvicultural treatments are applied. Unfortunately, the cost-effectiveness of even the comparatively well-studied RIL is not clear (55). Despite data scarcity, financial concerns probably explain why RIL and other sustainability promoting practices are not widely used, even in forests certified by international certification bodies (43). More generally, the expectation that voluntary third-party certification assures that forests are managed responsibly is not supported by data (56) and auditors are seldom equipped to assess STY (57). In the absence of adequate incentives, sensible forestry regulatory frameworks, and strong enforcement, managers are unlikely to invest in RIL or silviculture treatments especially where there are uncertainties about whether they will enjoy the financial benefits when the timber matures.

Considering the continued scarcity of climate change mitigation payments or other financial incentives for improved forestry practices, an often-recommended alternative to continued forest degradation by logging is to protect forests after the most valuable timber is harvested in so-called conservation concessions (58). Given that selectively logged forests retain many of their environmental values (7, 26), this approach to conservation makes sense unless the effects of activity-shifting leakage (i.e. displaced loggers harvest timber elsewhere) are too dire, the political price is unacceptable (e.g. loss of jobs in forest industries) or protection efforts fail. This pathway also disregards the admittedly seldom realized conservation potential of responsible forest management.

Conclusion

Clarity is needed about what is expected from managed forests and about the key components of STY. While plantations will likely supply an increasing portion of the demand for timber, tree farms cannot supply all the products and services provided by managed forests, and some favored timber species do not thrive in plantations. Most fundamentally, equating managed and degraded forests does not help efforts to reform the forest sector.

Where those responsible for forests are willing to accept the sequential depletion of timber stocks of different species with each harvest, then the costs of both harvest delays and silvicultural treatments are avoided and short-term profits from mining timber are maintained. Furthermore, if the over-harvested species are not critical for wildlife or ecosystem functions, then at least some of the impacts of sequential depletion are minor relative to those from intensification of management or forest conversion into plantations or other land uses. In contrast, if the goal is for harvested forests to return to their prelogging state in terms of timber volumes, trees sizes, and species composition, then operational specifications about STY are needed and timber industries will need to adjust to lower available timber volumes and lower profits. Fortunately, given that many of the silvicultural practices required for STY also serve to maintain and increase carbon stocks, climate financing should be available to promote economic and ecological sustainability.

Good decisions about STY require information about forest composition and structure as well as reliable estimates of rates of tree recruitment, growth, and mortality. These data, which are derived from repeated measures of permanent sample plots in selectively logged forest, can then be used to project future yields. While data scarcity at local levels remains a problem in many forests, regional data can suffice. The necessary monitoring is unfortunately expensive and reliable data come only from professionally established sample plots analyzed by competent biometricians. But no amount of growth-and-yield data can substitute for well-trained forestry personnel (6), which becomes increasingly challenging with the closure of so many university-based forestry programs (59).

Stabilization of timber yields is a common goal of land-use planners and investors in timber-based industries. Being able to predict future timber availability allows governments to formulate suitable policies and estimate future revenues, and timber industries to decide whether to downsize or expand, either of which has social and other consequences (e.g. employment, investment flows). Such predictions require clarity about STY.

Any effort to meet the criteria of a rigorous definition of STY reduces short-term profits, thus the shift from log-mining to forest management will require appropriate regulations along with incentives from governments and the private sector. Regulatory rigor is especially challenging in remote areas that are prone to lawlessness, but increased use of remote sensing methods can help. It would also help if timber from forests certified as responsibly managed fetched higher prices, but "green premiums" are rare (56). Compensatory climate change mitigation payments for forest management practices that reduce carbon emissions and increase carbon sequestration would be useful, but after 30 y of effort, such payments remain rare. Whatever combination of incentives and penalties are applied to promote STY, good governance is pitted against the long history of unsustainable logging motivated by short-term profit-seeking often enshrouded by corruption and illegality. Ambiguity about STY has not helped.

While environmental sustainability must remain a multidimensional aspiration with full recognition of its normative aspects, extreme caution is warranted when stocks of renewable resources are allowed to diminish. To avoid losses being overlooked, clarity is needed about exactly what is being sustained.

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Supplementary Material

Supplementary material is available at *PNAS Nexus* online.

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Authors' contributions

The paper was drafted by F.E.P. and then extensively revised by C.R., I.T., G.S., P.E., R., V.M, and P.S.

Data availability

All data are included in the manuscript and/or supporting information.

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