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Essential Variables help to focus Sustainable Development Goals monitoring

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The imperative to measure progress towards Sustainable Development Goals (SDGs) has resulted in a proliferation of targets and indicators fed by an ever-expanding set of observations. This proliferation undermines one principal purpose of the SDGs: to provide a framework for coordinated action across policy domains. Systems approaches to defining Essential Variables have focused monitoring of climate, biodiversity and oceans and offer opportunities to coordinate SDG monitoring. We propose four criteria and a process to identify Essential SDG Variables (ESDGVs), which will highlight interactions and gaps in current monitoring. The ESDGV criteria suggest a research agenda to: develop and test interdisciplinary system models; test transformations theory for sustainable development; analyse policy interactions; and formulate models to support further refinements of ESDGVs and SDG monitoring.

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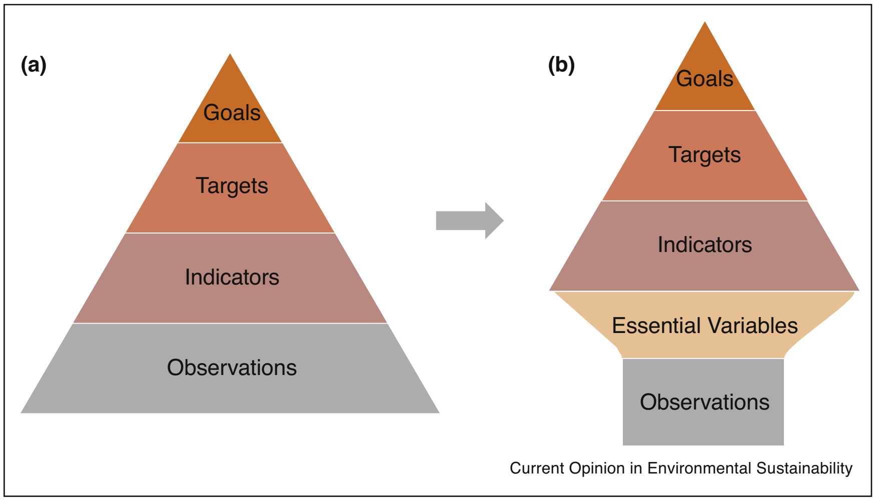
Challenging the proliferation logic of SDG monitoring

The world has recently agreed to 17 Sustainable Development Goals (SDGs), supported by 169 targets, in turn fed by an initial set of 230 indicators [1], each one of which relies on existing and new multiple data streams for its development (Figure 1a). Under this current proliferation logic, the process of developing an SDG monitoring system inexorably results in an ever-expanding set of observations which are certain to prove a burden for nation states [2,3]. The monitoring burden driven by this proliferation logic also increases the likelihood of uncoordinated monitoring by separate agencies, losing coherence as a result [4•].

There are over seven hundred multi-lateral environment agreements [5], and many more addressing social and economic development [6], all with their attendant monitoring schemes. One of the principal purposes of the SDGs [7] is to provide a framework within which action towards these various agreements can be coordinated [6,8•,9]. Thus, one might argue, the over-riding priority for SDG-specific monitoring systems should be to inform this process of coordination [4•,10]. Instead of a proliferation logic that says "The SDGs encompass many areas of activity and they all need to be monitored and reported on under the SDGs process", the logic could then become one of coordination: "The SDGs monitoring process should focus on ensuring coordination and fill important gaps among the many areas of activity that have their own individual monitoring processes".

In moving towards a more coordinated logic for SDG monitoring, advances in systems theory (*e.g.* [11–14]) offer potential ways to structure such a monitoring system. One systems approach is Essential Variables (EVs; Table 1) which has arisen to prioritise and coordinate the monitoring of climate [15••], biodiversity [16••] and oceans [17••], and which is an area of active research and application in other communities (see next section). EVs are the minimum set of variables required to characterise change in a system. The purpose of this contribution is to review the potential for the EV approach to limit the tendency towards proliferation in monitoring for the SDGs and refocus effort on a coordinated system. We also identify the transdisciplinary research agenda that would be required to support such a development.

Figure 1



The introduction of Essential Variables (EV) as a layer between primary observations and indicators can transform the shape of monitoring systems from (a) an ever-broadening pyramid to (b) a more streamlined form. In (b) a limited number of EVs, directing a targeted set of repeatable and universal observations, underpin a changing superstructure of policy-relevant indicators, targets and goals. The EV layer insulates the observation levels from the changing policy priorities, and makes the policy indicators independent of the observational platform. It further harnesses systems understanding so that a single EV capturing a key process or structure can potentially contribute to multiple indicators, while similarly 2 or more EVs can direct and use the same primary observations, thus potentially enabling a reduction in the numbers of observations needed to deliver those indicators.

The Essential Variables approach to monitoring complex systems

The concept of Essential Variables was first used by the Global Climate Observing System (GCOS) in the 1990s. It defined essential climate variables (ECVs) as "physical, chemical, or biological variables or a group of linked variables that critically contributes to the characterization of Earth's climate" (GCOS 2010). The ECVs were proposed as a response to the need for a more coordinated approach to global climate observations [15••,18]. Criteria to identify ECVs included relevance in characterizing the climate system and its changes, feasibility of observing and deriving the variables, and cost effectiveness. The ECVs have been widely endorsed in both science and policy circles. The ECV process, guided by regular reviews and updates, continues to evolve in response to changing priorities, needs, new knowledge and innovation [15••].

Ocean scientists adopted a similar approach under the Framework for Ocean Observing, leading in 2010 to community-defined Essential Ocean Variables (EOVs) [19]. The EOVs process included the criterion of the 'readiness level' of the observations, allowing the inclusion of new observation types in an iterative way with regular feedback loops (*e.g.* [16••]). Similar processes have since been followed within the biodiversity observation community, leading to the Essential Biodiversity Variables (EBVs). These are defined as "essential dimensions of biodiversity change" [16,20–23]. The EBV approach further clarifies that Essential Variables "lie between primary observations and indicators" [24]. This level of

Table 1

List of acronyms describing Essential Variable types including their status of development

Acronym	Description	Status
EV	Essential Variables	
ECV	Essential Climate Variables	Existing
EBV	Essential Biodiversity Variables	Existing
EOV	Essential Ocean Variables	Existing
ESocV	Essential Social Variables	Some existing, but not described as such
ExxV	Essential Variables for missing domains	Proposed for domains not yet thinking in this way that may need collecting under SDGs
ESDGV	Essential Sustainable Development Goal Variables	Proposed entire set of EVs for the SDGs
core ESDGV	Core Essential Sustainable Development Goal Variables	Proposed core set of EVs not collected within sectors, focused on sectoral interactions, transformations and in the social-ecological interface.

abstraction provides a degree of independence from observations, thus accommodating multiple diverse primary data streams across regions and sections, as well as the flexibility to meet changing demand for indicators in response to multiple dynamic global monitoring and policy needs. To constrain the variables to a manageable number, EBVs are limited to biological variables of state. Additional criteria of sensitivity to change and applicability across multiple domains also apply. The conceptual framework of EBV classes and candidate variables helps guide a consultative, expert-based and online process of development [24]. Additional ideas are explored for marine ecosystems [25••].

Although not described in the 'Essential Variables' language, other studies have employed systems frameworks and transdisciplinary processes to identify variables capturing critical dimensions of the earth system [26,27••], including its biophysical sub-systems such as primary production, biogeochemistry and freshwater [28–31]. Beyond the biophysical domain, researchers have recently begun to identify critical social determinants of development targets including health [32] and nutrition [33], and refined these determinants based on their feasibility, reliability, validity, and usefulness to policymakers. Other systems approaches and composite indices [34–36] highlight important social and economic dimensions for tracking progress to development targets. Methods such as the footprint approaches (*e.g.* [36–42]) and socio-ecological metabolism and modelling approaches (*e.g.* [35,43,44••,45•]) extend this systems thinking to areas of interaction between the social and biophysical domains, as do ideas such as the 'safe and just operating space', which links environmental, social and economic dimensions explicitly (*e.g.* [46•,47••]).

While not all at the same levels of development or resolution, these areas of progress in systems and sustainability research identify essential dimensions or variables of social, economic and biophysical systems change. Consequently, they present an opportunity to focus monitoring efforts and to radically transform the current shape and scope of monitoring systems (Figure 1). Not only can EVs focus monitoring systems for more efficient observations, but also, because they capture key system dimensions, one EV can potentially contribute to multiple indicators, and the same observation can link to more than one EV, thus potentially enabling a reduction in the numbers of observations needed to deliver those indicators (Figure 1b). For example, the EBV of taxonomic diversity directs the observations of multitaxa surveys at select locations, and in turn supports two Convention on Biological Diversity (CBD) indicators. Those same surveys of species relevant to ecosystem services can support another EBV on species abundance and distribution, which in turn feeds into seven different CBD indicators on species and population trends [16••].

Criteria for selecting Essential Variables for the SDGs

The EV processes for climate, oceans and biodiversity reveal a range of criteria for defining what is essential. For the SDG domain these criteria need further development. Adding the desire to coordinate between policy domains, there are at least four possible and overlapping criteria for identifying variables essential to the SDGs, including those which:

- *Capture system essence*. Based on knowledge of social–ecological systems, which key features, processes and interactions are critical for describing and projecting their behaviour over time and space? (cf. [16••,18], but recognising the added scope of the SDGs).
- *Link to system transformations*. Does the variable support the transformative agenda of SDGs, based on our knowledge of system transformations and leverage points? (*e.g.* [48•,49•,50,51]).
- *Capture key areas where coordination is needed*. Does the variable capture trade-offs or synergies between the SDGs or between policy arenas requiring coordination, especially those where coordination is weak? (cf. [4•,6,9,52]).
- *Are indispensable*. Is the variable foundational and multipurpose for tracking sustainable development? (cf. [16••,17••])

All criteria require a conceptual model of how systems function at the level of global sustainability and human well-being (*i.e.* a set of components and interrelationships, forming a complex causal hypothesis of how systems work). There is not (and may never be) consensus on a single systems model encompassing the entire scope of the SDGs. As a first step in the process of Essential Sustainable Development Goal Variables (ESDGV) development, there is a need for an expert driven, practical approach to draw on existing subsystem models (*e.g.* biophysical, social, economic) and emerging integrated system models and frameworks to represent the whole linked social–ecological systems of global sustainable development. The process requires deliberate consideration of these diverse lenses and models (*e.g.* [35,44••,53••,54,55•,56••,57]).

Criterion A is applied based on these interdisciplinary models through the identification of essential components and flows of relevance to the system and its sustainable development. Although differences in model conceptualization and detail prevail, they share the notion of needing to represent ecological and social (or sociocultural) *systems*; the *links* between systems, including material and non-material forms of interactions and feedbacks; and within and cross-scale *linkages*, as well as the *dynamics* of these systems [44••,58,59•]. Recent progress in conceptual frameworks of the Intergovernmental

Platform on Biodiversity and Ecosystem Services (IPBES [56••]) and the conceptual approach of the Vienna Social Ecology School [53••] offer useful analytical starting points to apply Criterion A and represent these key aspects of systems (Figure 2).

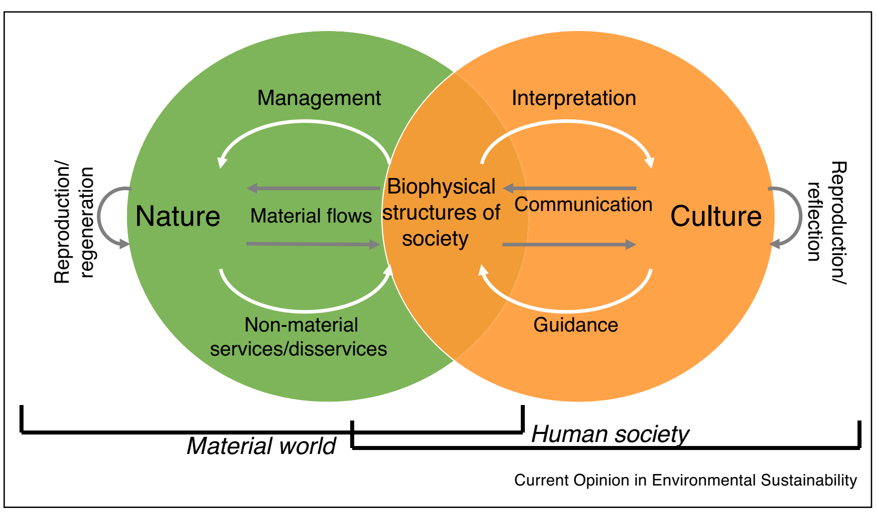
Criterion B also requires a system model, but focuses on points of leverage where actions can be prioritised in order to drive specific transformations. Work identifying the key transformations needed to drive the 2030 agenda provides the focus for this criterion (*e.g.* [50,51]). ESDGV selection can be informed by the system model (Figure 2), noting that changes in the cultural system, reflexive communication, and the guidance of decisions and practices, have the potential to 'transcend paradigms' and trigger transformation to sustainable development [54,57,58]. Other frameworks (*e.g.* [49•]) help to identify variables of the system that could potentially be altered in a transformation, and support the identification of barriers and leverage points for transformations, for example for lower income nations [51]. This work also highlights variables that may be associated with reinforcing feedback loops that can release a system from an undesirable trajectory (*e.g.* [60]), as well as aspects of transformative capacity and timing [61–63].

Criterion C emphasises the coordinating purpose of the SDGs towards integrated implementation across policy domains [4•,9,64••]. This may be approached by considering what variables are needed to deliver to critical indicators (*e.g.* [65]), or by systematically examining the linkages among existing targets [9,52], or by analysing the relevant policy instruments themselves [6]. Criterion C offers an opportunity to review the current list of SDG indicators and assess the list of Essential Variables required to support them. However, by itself this would be an overly narrow analysis that would miss underlying system drivers and causal factors affecting interactions between goals.

Criterion D is informed by more operational concerns—those variables which are required for multiple purposes: they are at the nexus of many processes (*e.g.* demographic or land use variables) and are thus foundational. This of course again requires some systems understanding, now focused on how a small set of variables can predict key aspects of system behaviour. This criterion was pioneered by the ECVs [15••].

There is no current rationale to say that any of Criteria A–D is strictly better or worse than the others, nor that any is redundant or mutually exclusive. Pragmatically the literature indicates that the ESDGVs should be defined as those that emerge from at least one of these four criteria, thus suggesting an iterative process that we explore in Box 1. Once a combination of the above criteria has been applied, there are some additional operational criteria that can help to select among candidate variables, such as

Figure 2



An integrated socialsocial–ecological systems model [53,56] based on an explicit theory of social–ecological coevolution of nature and culture. Nature and culture are linked through the flow of material and non-material effects (and feedbacks) that occurs between nature and biophysical structures of society. The biophysical structures of society include the human population, the built environment, as well as other material assets (*e.g.* livestock) that determine access to services and distribution of benefits and wellbeing. These flows are co-determined by natural and social processes, and are shaped by the cultural system of laws, norms, values, knowledge and beliefs. The links between the biophysical and cultural systems of society are mediated by 'communication', that is the reflexive processes of information exchange, interpretation, and understanding which can include legal, economic and monetary processes. Communication allows for the development of practices and institutions, reflection and adaptive learning that guides decisions and actions in the biophysical realm, with resultant impacts on natural processes. Agreeing on a useful (though not necessarily prescriptive) conceptual model of this nature is a key step in developing ESDGVs.

minimalism, unambiguousness, universality, scaleability, sensitivity, stability, and efficiency (see Ref. [17••]).

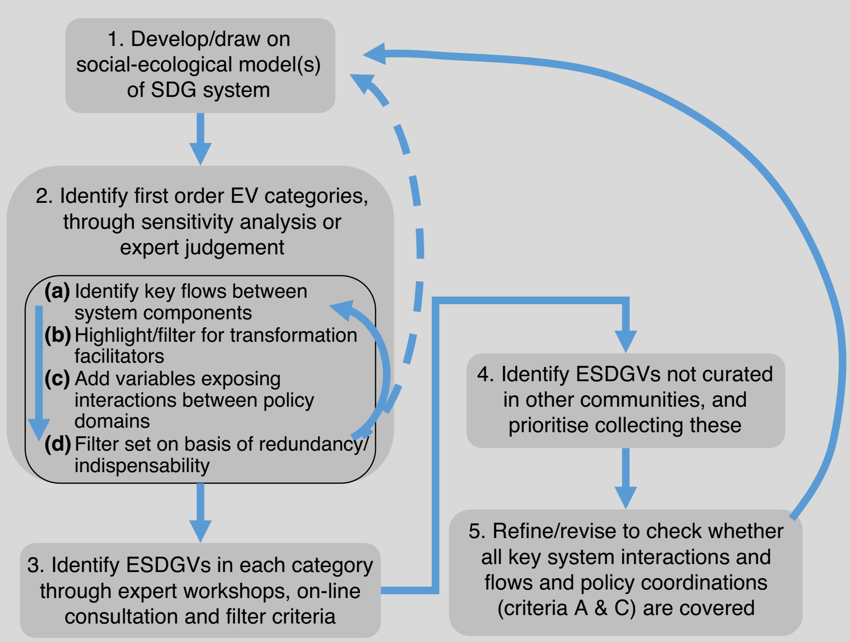
What could resulting ESDGVs look like? A representation such as Figure 2 facilitates the application of transdisciplinary knowledge to iteratively apply the above criteria in identifying the multiple dimensions involved in delivering on the SDGs (Box 1). Importantly, the model fosters a more integrated approach coordinating across goals and targets, clustering related SDGs, rather than examining one SDG at a time. Such clustering could be based on the six transitions suggested by Osborn *et al.* [51], or in other ways. As an illustrative example:

- The energy transition depends on coordinating the delivery of 'energy for all' (SDG 7) with limiting emissions of CO_2 (SDG 13). Analyses have shown that ESDGVs on energy supply, sources and demand, carbon emissions, and resultant economic outputs would be relevant to tracking energy and carbon intensity [66]. Further ESDGVs on household energy access and source would track universal access (and health) trends in priority regions [67]. Figure 2 further reminds us that the transformational changes needed in the energy system will not be achieved without paying attention to the social systems and their biophysical and cultural components, leading to potential ESDGVs on the extent of regulatory changes, (renewables) infrastructure and investments, and changes in norms around consumption and distribution [66].
- Similarly the food transition involves meeting food security (SDG 2), health outcomes (SDG 3) whilst improving water and land use sustainability (SDGs 2, 6, 15), including reducing polluting run off into inland waters and oceans (SDG 2, 14). This suggests ESDGVs of nutrient yields, land use change, flows of water, P and N inputs, and food security and food access as some of the key system variables [68]. But the transition itself will be promoted by societal changes related to food choice, reducing food waste, and access to (healthy) food. All these will be affected by food pricing but also by meta-narratives around diets and health that may affect shifts to or from meat dominated diets [69,70]. The latter suggest other

Box 1 Proposed steps in a co-design process for ESDGVs

The process to develop ESDGVs must be iterative, evolutionary and transdisciplinary. It must employ multiple approaches and lenses, alternating between systems-oriented steps and domain-specific filtering based on operational criteria. In practice this could be achieved through workshops and syntheses focused in broad areas of the SDGs (*e.g.* around each major transition of [50,51] alternating with higher level consolidations across all the SDGs).

The Figure (below) outlines such a process; the arrows indicate how it is strongly iterative. Step 1 adopts one or more conceptual or quantified social–ecological models of the system encompassed by the SDGs (see main text). Similar to the EBV process [15], Step 2 initially identifies broad categories of ESDGVs, using criteria A-D (see main text), within an inter-disciplinary systems consultation and design phase. This then sets the scene and direction for a broadly engaged, disaggregated input of potential variables (Step 3; also Figure 3). These are subject to further systems sifting, refining, prioritizing and development (Step 4). Finally, a learning loop on the whole process is crucial, given the complexity of the challenge (Step 5). This should be closely aligned with the further development and policy use of the SDGs.



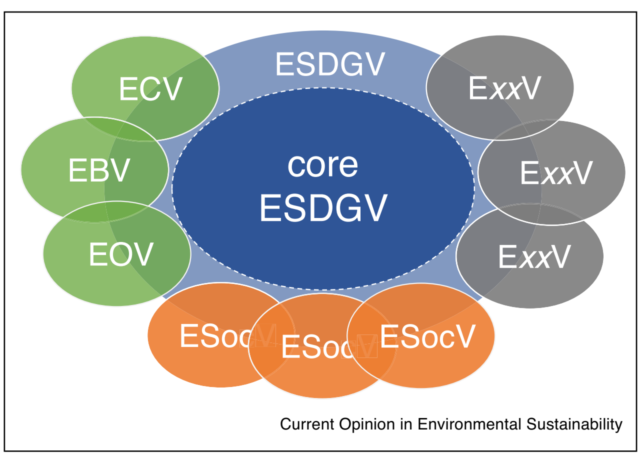
ESDGVs to track the effects of changing awareness and behaviour on diet-health links in different countries and cultures.

An applied research agenda

The rationale for developing EVs in general has been to focus and direct monitoring efforts, as well as to make the monitoring system more internally consistent and free of critical gaps (*e.g.* [16••]). In the case of the SDGs, an added impetus should be to meet the original intent of 'orchestrating' the diversity of policy domains affecting and affected by the goals [6]. As Figure 3 suggests, there will be EVs needed for specific decision or policy domains (whether or not they are currently recognized as EVs). However, the core set of ESDGVs should emphasize those variables that are critical for achieving the higher level objectives of the SDGs—to transform towards sustainable development and to coordinate among policy domains. This will often draw on EVs from individual domains, but also identify those that would be missed in a fragmented approach.

Notwithstanding this logic, the process proposed in Box 1 requires a number of advances in our understanding of the system of sustainable development. These will be best achieved through an applied research agenda, which consciously explores the following issues in the course of implementing the whole process iteratively (Box 1). Some critical research needs for each criterion are:

Figure 3



Various areas of global policy development are defining their own Essential Variables (in green), including some social variables (ESocV—in orange) that do not use this terminology (*e.g.* for poverty, inequality and economic performance). Additional Essential Variables for sectors not yet thinking this way may need collecting under the SDGs (ExxV—in grey). The total set of Essential Sustainable Development Goal Variables (ESDGV—in blue) would draw on and initiate some of these domain-specific Essential Variables (outside dashed circle), while the core set of ESDGV (inside dashed circle) would focus on Essential Variables not collected elsewhere by specific sectors, that support transformations, interactions and coordination among the domains that might otherwise be missed.

Appropriate system framing(s): Criterion A requires advances in conceptualizing the multi-level, integrated global system that links the social, ecological and economic components of the SDGs, to include issues as diverse as water flows, food security, legal systems and peace, and importantly the interactions and feedbacks between these, as well as their distributional effects across space and time. Building on Figure 2 and other approaches (*e.g.* [43]), with components potentially further explored in models or formalisations [55,65,71], the ESDGVs process presents an enormous opportunity to integrate our interdisciplinary understanding of the global system, and to hypothesise, test and learn about essential dimensions of this system.

Transformations to sustainable development: Criterion B requires advances in understanding which elements of a system will most drive transformations (*e.g.* see Refs. [72••,73,74]), which transformations are required to achieve sustainable development (*e.g.* [51,75,76]) and allow us to test theory on transformative capacity, agency, innovation, as well as barriers to and levers for transformation in the arena of global sustainable development[8] [48•,49•,63,75,77].

Analysis of critical policy coordination needs: To inform Criterion C, the suite of policy instruments [5] needs to be formally catalogued and mapped as to their needs for coordination, in collaboration with the UN system. Work by the Convention on Biological Diversity to map its policy targets against the SDGs is an example,[9] also illustrating how EBV development could support ESDGVs (cf. Figure 3).

Assessing the importance of variables: For Criterion D, ideally, models of the system will be developed through a combination of quantitative inputs, expert opinion, stakeholder co-design, and broader forms of uncertainty analysis to allow sensitivity testing, in order to identify variables that underpin and are most sensitive in system change (*e.g.* The World in 2050[10] project).

As suggested in Ref. [4•], a well-formulated set of ESDGVs could form the basis for a Common Standard for reporting across the private and public sectors, locally to globally, that helps to standardise our understanding of, and response to, progress on sustainable development. The United Nations' 2030 Agenda is intended to have a reflective learning cycle supported by the Global

[8] http://www.worldsocialscience.org/activities/transformations; http://futureearth.org/future-earth-transformations.

[9] UNEP/CBD/SBSTTA/19/INF/9, 22 October 2015: *Links Between the Aichi Biodiversity Targets and the 2030 Agenda for Sustainable Development.*

[10] See http://www.iiasa.ac.at/web/home/research/researchProjects/TWI2050.html: seeks eventually to integrate a new generation of models from social and environmental spheres to explore what the world may look like if SDGs are (or are not) achieved.

Sustainable Development Report and the deliberations of the High-Level Political Forum[11] of all member states over the life time of the SDGs, to provide an adaptive governance approach to this vital global initiative. Key to such deliberations is a more profound framing of how the cultural system is dynamically linked to material society in the context of SDGs. The research needed to catalyse the definition of ESDGVs would also help to crystallise the priorities of these adaptive governance processes towards a more focused monitoring and learning system driving transformation whilst coordinating diverse policy interests.

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