Making sustainability science a cumulative effort

In light of pressing societal and environmental problems, sustainability science must advance faster than before. In order to contribute to a cumulative body of knowledge, such research needs shared infrastructure, database development and changes in research culture.

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Sustainability scholars study human–environment systems and in doing so they face several challenges. The systems they study are complex and characterized by unpredictable linkages across processes and agents not yet fully understood[1]. Research to understand the impacts of the large-scale roll-out of sustainable development strategies needs to incorporate the insights from sustainability science to comprehensively inform decision-makers about issues such as the sustainability of planned biofuel production or the efficacy of emissions trading or carbon taxation schemes. For such effort we need an interdisciplinary scientific approach, for which a new research culture and infrastructure to facilitate method and data integration are needed. Because of their relevance to society, both sustainability science and research for sustainable development are exposed to intense public scrutiny and critique which entails additional transparency and communication challenges. Despite examples of successful collaborations, when scholars engage with non-academic partners, they face difficulties as government agencies, consultancies and non-governmental organizations (NGOs) do not naturally see open dissemination of the scientific knowledge created as their main priority. For example, socio–metabolic data such as inventories of industrial processes or product material compositions are often confidential or simply not available, which forces researchers to make compromises on the transparency of their research or simply precludes research efforts from the start.

Current pay-wall publishing, poor data reporting practices, and sometimes low standards for conducting sound and reproducible research are further barriers to knowledge accumulation and thus slow down progress[2,3]. For many published claims, the raw data, software used, and sometimes even basic assumptions such as system boundary choices (that is, which processes and effects are included in a study and which are not) are not well documented, for example, in life cycle assessment[4], which at times abets biased and agenda-driven research and precludes impartial reproduction of the claims made. Often, with complex modelling efforts, such as in the case of many energy system models[5] and some integrated assessment models[5] used to analyse the transformation of society's energy supply and industrial basis, data handling and the software tools used are rarely scrutinized during peer review or other form of independent quality control. It is therefore often impossible for scholars and outsiders to validate, compare, or just reuse the quantitative results of technology assessments or scenario analyses. The reproducibility crisis[6] persists in the sustainable development scholarly domain as well as in other domains. Consequently, a large body of repetitive research, incompatible datasets and opaque modelling tools have accumulated over the last decades. Some of the data generated and tools developed cannot be improved or reused. Hence, they do not contribute to a cumulative body of scientific knowledge. The prevalence of limited consultancy-type funding, the tendency to publish in small units and the recurrence of short project time frames mutes incentives for cumulative data compilation and refinement as well as development of transparent methodology.

Over the long term, the above-listed barriers to knowledge accumulation in the participating disciplines will curtail the impact of sustainable development research.

Table 1 | Measures and infrastructure needs for cumulative sustainability science

Research cycle stage	Measure	Infrastructure and other kinds of intervention
Framing, data gathering and method selection	Make an effort to use and expand existing analysis frameworks. Scan data, methods, tools and transdisciplinary experience available. Use stakeholder consultation. Use multi-model case studies.	Research framework catalogue. Data, method and toolbox inventory; transdisciplinary project catalogue. Stakeholder networks mapping. Model inter-comparison.
Data handling and formatting	Use or expand existing data models. Contribute to linked datasets with common classifications. Use common classifications. Deliver formatted data.	Consensus data models. Conversion of data to linked open datasets, database integration. Standard classifications. Data templates and parsers.
Analysis tool development and use	(Re-)use and develop modular analysis tools. Contribute to peer-reviewed tools. Test modular tools. Provide best practice examples.	Strategic tool development and refinement across disciplines. Facilitate the development and refinement of interfaces between modules. Distribute testing efforts, blind testing. Provide platform for identifying sharing best practice in research.
Dissemination of results	Document research procedures, including assumptions and judgements in qualitative research. Make analysis traceable: interactive visualization. Make results available: database.	Provide research protocols. Interactive visualization platforms. Expand databases for primary and modelled data.

Develop research infrastructure

We need better research infrastructure combined with a different working

Box 1 | Responsibilities for knowledge accumulation in science for sustainable development

Early career researchers
- Awareness: critically reflect the purpose of your work and learning efforts.
- Connect to existing efforts: expand and improve existing frameworks and tools, provide documentation and demand high quality tutorials and teaching/training.

Established researchers
- Lead by good example.
- Set up codes of conduct for sharing and tools, frameworks and experience from action-oriented research.
- Supply tutorials and teaching/training material.

Editors and reviewers
- Provide examples and guidelines for method and data transparency, reproducibility and proper data archiving.
- Insist on method and data transparency, reproducibility and proper data archiving.

Publishers
- Highlight and reward sound contributions to cumulative science.
- Allow for preprint archiving of manuscripts.
- Provide access to supplementary material in any case and exclude it from copyright transfer (for pay-wall publishing).

Research associations, societies and communities
- Develop guidelines for reproducible research and proper data archiving and experience sharing.
- Monitor and inventory the state of the research (frameworks, methods, tools and data).
- Review successful infrastructure development projects in other disciplines.
- Map research infrastructure needs and support its implementation.
- Host research infrastructure where appropriate.
- Facilitate exchange formats on cumulative research (workshops, fora and special sessions).
- Reward salient contributions to cumulative science.

Funders
- Enter a dialogue with research communities regarding cumulative science.
- Offer funding channels for research infrastructure in sustainability science.
- Demand method and data transparency, reproducibility and proper data archiving.

Societal stakeholders
- Demand transparent and reproducible knowledge generation on sustainable development strategies.
- Demand efficient use of research funding for science for sustainable development.
- Identify or set up bodies to host research infrastructure.

culture in order to speed up knowledge accumulation in sustainable development research. We do not have to build from scratch. There exist examples from which the community can learn. The Energy Modelling Forum, for example, seeks to improve the use of energy and environmental policy models for making important corporate and government decisions, by harnessing the collective capabilities of multiple models. This has ultimately led to major contributions to the latest Intergovernmental Panel on Climate Change (IPCC) reports by the integrated assessment modelling community[7,8]. The Global Life Cycle Assessment Data network (GLAD) aims to achieve better data accessibility and interoperability for life cycle inventory datasets from different providers. The Consortium of European Social Science Data Archives (CESSDA) provides large-scale, integrated and sustainable data services to the social sciences, bringing together social science data archives across Europe. Finally, the Social Sciences and Humanities Open Cloud (SSHOC) aims to provide a comprehensive open cloud infrastructure, where data, tools and training are available and accessible for researchers to stimulate multidisciplinary collaboration across the various subfields of the social sciences, humanities and beyond, to increase the potential for societal impact. By facilitating a dialogue across the research communities involved and by (financially) encouraging knowledge transfer, experience from these and related infrastructure projects can be transferred to research communities and associations that plan to develop their own infrastructure in order to produce knowledge accumulation.

There are steps to take in order to achieve knowledge accumulation along all stages of the research cycle and for both quantitative and qualitative research (Table 1). These are well known, and we need to implement them more widely and integrate them into larger development plans in order to have lasting impact on the working culture. Measures pertaining to data and quantitative analysis tools are of particular importance and described in more detail below.

Database for research

Using and updating data needs to become easier than it is now. A comprehensive, open and continuously updated database speeds up quantitative assessments and facilitates scientific consensus. By storing different versions of the same datasets, previous research findings can be reproduced exactly and updated. More research data should be publicly available[9], curated, and if necessary made anonymous, including information about supply chains, technology descriptions, product composition, environmental impacts and commodity prices. We need to stimulate a wider dialogue to answer the question, "Where is the boundary between public interest in information and protection of businesses?" when it comes to what sustainability-relevant information and insights society should have general access to. Data extraction, processing and storage are becoming more and more automated and thus cheaper to apply and replicate, but they are hindered by restrictive or unclear licensing of available data. Standards for how to share and licence data and databases that contain a mix of primary and secondary data need to be developed. Research communities should raise data transparency standards[10].

Method development

Researchers should compile and distribute best practice examples across the branches of sustainability research, so that undergraduate and graduate students can quickly reach the standards in the field. These examples should include mathematical descriptions, data formatting standards, sound computer code, and visualization, logging, documentation and testing routines. Analysis tools should be open source, modular and build upon available unit-tested software code. Reviewers need to insist on proper documentation of research procedures, including in the context of policy-relevant research and consulting. Funders need to establish and enforce method transparency standards on research published in grey literature reports, without peer

review (for example, EU Horizon 2020 projects). We need ways to perform multidisciplinary multi-model assessments and method triangulation, as well as greater interoperability between data and software/models. Cross-model and cross-disciplinary comparison should be the norm when developing policy-relevant recommendations wherever suitable models are available[11].

Responsibilities of actors

The solutions to the structural problems of the sustainability research domain need to be both community-driven and stakeholder-driven to create permanent incentives that can lead to structural change within the scholarly community (Box 1). Scholars need to embrace the need of making cumulative science the new norm within the sustainability domain. Journal editors and reviewers can drive change by requiring authors to disclose more details about their work, and make their results more useful to others, including software[12]. Scientific societies and academies should offer multiple forms of guidance and support for knowledge accumulation. Established researchers should supply teaching material and best practice examples, as well as develop canonical research problems and open tools to solve them. Such efforts would also make it easier for upcoming researchers from developing countries and specifically the Global South to make sound contributions. Many of the proposed measures fit under the open science label[2,13], especially those relating to the availability of procedures, data and results[14].

Maturing disciplines

Funders and research managers need to realize that sustainability research, which is mostly interdisciplinary, is no longer conducted as an offspring from traditional disciplines but now mainly happens in dedicated communities such as energy system modelling, integrated assessment modelling, sustainability economics, industrial ecology, or life cycle assessment, to name only a few. These research communities are conducting their own fundamental research, developing their own scientific methods and standards, and need more support for building up the infrastructure that allows them to advance science for sustainable development in a transparent and cumulative manner, that is, by pursuing ambitious interdisciplinary and collaborative research agendas[15]. Research funders should therefore put more emphasis on supporting efforts that contribute to a cumulative and shared knowledge base to allow for meaningful allocation of financial resources[16].

The way forward

A major hindrance to more cumulative research is that the 'business model' of many research groups and non-academic institutions is based on exploitation of proprietary data and closed source models. Against the background of the global challenges we face, scientists and funders have a common responsibility to find the right balance between competition and cooperation regarding both data licensing and tool development. A broad debate on how sustainability research should function in the future is needed to make sure it continues to provide robust insights that are being implemented[17] (as an example, see Spoelstra[18] for a discussion on organizational challenges for interdisciplinary research on sustainable agriculture). Facilitating knowledge accumulation in sustainability science and research for sustainable development is a central strategy that will help strengthen the role of scientists as honest brokers in sustainable development across the globe. ❐

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