Speaking of success: Real-world experiments for sustainability transformations and causal inference

Reports of successful sustainability-oriented real-world experiments can be categorized by the type of explanatory approaches employed, namely, the variance approach, which looks for correlations, and the process approach, which draws causal inferences in a narrative way. Their validity could benefit from a more critical reflection on the data and methods used.

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Abstract
This paper examines a sample of 20 sustainability-oriented real-world experiment reports from 2006 to 2020, with the aim of uncovering the logic and methods used to demonstrate their success, that means, to show that they achieved their stated objectives. Following a distinction often made in the social sciences, I look for features of either the variance or the process approach to causal inference. I find that reports of transition experiments, socio-technical experiments, and community-based interventions display characteristic features of the process approach. Reports of trials, pilots, and field experiments, on the other hand, mostly use the variance approach to demonstrate success. An important observation is the limited recognition of possible biases related to the methods used or the data. I describe a number of possible biases that may be of importance in the context of sustainability-oriented real-world experiments. Important examples include measurement errors and biases in participant selection. Recognising the biases and correcting them where necessary can strengthen the validity of the findings obtained and help other researchers in designing their experiments.

Keywords
biases, causal inference, process theory, real-world experiments, sustainability transformations, variance theory

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Why revisit real-world experiments?

In recent years, real-world experimentation in its diverse forms has become popular among both researchers and practitioners in search of new insights for sustainability transformations in cities and regions (Ehnert 2023). A particular focus in the research employing sustainability-oriented interventions has been on how evidence-based actionable or transformational knowledge can be produced (Caniglia et al. 2017). Without doubt, it is important that the produced evidence about the causes of sustainability problems as well as about the effectiveness of solutions fulfil the criteria of scientific soundness and validity. Related to this, there have been repeated calls (Kivimaa et al. 2017, Schäpke et al. 2018, von Wirth and Levin-Keitel 2019, Williams and Robinson 2020) for concepts and approaches to evaluate experiments in terms of effectiveness in achieving sustainability-related objectives. Similar debates about design features allowing the comparison and evaluation of experiments have been carried out earlier in other disciplines employing experiments in a real-world setting, such as economics (Harrison and List 2004) or sociology (Cook and Campbell 1979).

In this paper, I aim at addressing one particular aspect, which in my view currently remains understudied. It is the issue of (the possibility of) causal inference through real-world sustainability-oriented experimentation, including challenges related to the quest for distinguishing cause and effect in this context. This is done by revisiting a number of cases that were previously cited as examples of "successful" experiments. I also aim at connecting the literature on sustainability-oriented experiments and the literature on real-world experiments in other fields, which seem to have low mutual recognition to date. In particular, this concerns the practice of dealing with biases in the data and methods. The research questions addressed in this paper are:

- Which explanatory approaches can be identified in the studies that describe sustainability-oriented real-world experiments?
- Do the different types of experiments differ in terms of explanatory approaches?
- How do the studied experiment reports address caveats in the methods and the data?

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TABLE 1: Results of the review of experiment reports described in this paper. The first group uses the variance approach (e.g., via statistical methods) to demonstrate experiment success. The second group uses narrative-type explanations consistent with the process approach. The third group cannot be assigned to any of the two methods. For each report, experiment type, success definition, and attributes of the explanatory approach are indicated. [C] = from Caniglia et al. (2017); [L] = from Luederitz et al. (2017); [K] = from Kampfmann et al. (2023).

REPORT	EXPERIMENT TYPE (NAME)	SUCCESS DEFINITION, ACHIEVED OBJECTIVES	ATTRIBUTES OF THE EXPLANATORY APPROACH
VARIANCE APPROACH			
Adkins et al. (2010) [L]	pilot (Millennium Villages Project lantern trial, MW)	more durable and bright lighting	survey on lighting patterns before and after LED lantern purchase, regression analysis
Baedeker et al. (2014) [C]	living lab/trial (SusLabUK, London, UK)	reduced energy consumption	data collection through sensors and surveys before and after intervention, statistical analysis
Cole and Srivastava (2013) [L]	living lab/trial (Yale campus, US)	replacing metal halide lamps with LED lights in parts of campus	data collection on hours of excess usage, cost-benefit analysis of alternative systems
Liedtke et al. (2015) [C]	living lab/trial (SusLabNRW, Bottrop, DE)	reduced energy consumption	data collection through sensors and surveys before and after intervention, statistical analysis; validation
Andersson (2015) [K]	field experiment (smallholder farmers, UG)	improve soil fertility for maize production	control plot, several interventions with fertilizers, statistical tests for yield differences, SWAT analysis
Plaisier et al. (2019) [K]	pilot (tomato value chains, NG)	reduce postharvest losses by using plastic crates for transport	conventional technology as a control, measurements, evaluation workshop
PROCESS APPROACH			
Miller et al. (2015) [L]	community engagement experiment: (Community Watershed Stewardship Program [CWSP], Portland, US)	Only projects that meet equity targets are funded.	descriptive analysis of grant applications before and after change of funding scheme, process description
Wiek and Kay (2015) [L]	pilot (Solution-Oriented Sustainability Learning [SOSL] program, Phoenix, US)	Students acquire new knowledge, contribute to developing transformation strategies.	comparison of alternative course designs, participant reflexions, extended peer review
Geels and Raven (2006) [C]	strategic niche experiment (biogas development, NL)	Diffusion of biogas plants as a result of strategic niche management.	longitudinal study, document analysis, interviews with involved actors
Smith et al. (2014) [L]	socio-technical experiment (grassroots innovation movement, BR)	self-build water harvesting technique diffused	process description, document analysis
Ceschin (2014) [L]	socio-technical experiment (Cape Town Sustainable Mobility project, SA)	introduction of mobility service for elderly people (one vehicle prototype)	process description
Loorbach and Rotmans (2010) [L]	transition experiment (District Care, NL)	Transition agenda delivered, service growth documented, customer satisfaction increased.	comparative evaluation of service quality, process description
Wittmayer and Schäpke (2014) [C, L]	transition experiment (community arena, Rotterdam, NL)	ownership of the process by the arena participants, self-maintenance of the community	reflective monitoring interviews, an evaluation meeting, process description

Bos and Brown (2012) [L]	transition experiment (Cooks River Sustainability Initiative, AU)	increased appreciation of urban water management, establishment of a formalized political association	interviews, focus-group discussions, process description
Mačiulienė and Skaržauskienė (2020) [K]	living lab (Art Factory Loftas, Vilnius, LT)	strengthen the involvement of senior citizens in social activities through digital tools	observation, interviews, questionnaires, digital monitoring
Hubeau et al. (2017) [K]	sustainability experiment (Locally-Grown Soybeans, Flanders, BE)	collaboration success: perceived social gains, perceived transformative power, perceived learning effects	reflective evaluation, workshops, document analysis, in-depth case study analysis, validation through triangulation
INSUFFICIENT EVIDENCE			
Bernstein et al. (2014) [L]	community engagement experiment (collaborative tree and shade intervention, Phoenix, Arizona, US)	creating and maintaining a community garden (intervention [trees planting] did not yet happen at the time the report was published, crucial caring phase not started)	concept discussion, process description
Frantzeskaki and Tefrati (2016) [L]	transition experiment (Aberdeen's Transition Management, UK)	actionable knowledge, lessons for governance of urban sustainability transitions (arena process not yet finalized)	interviews with transition arena participants, process description
Trencher et al. (2013) [L]	pilot (gas-fuelled taxi project, 2000 Watt Society Pilot Region Basel, CH)	scalability of the project (no evidence of diffusion at the national level beyond Region Basel provided, gas-fuelled taxi project terminated)	statements from key stakeholders, process description
Voytenko et al. (2016) [L]	urban living lab (New Kiruna City, SE)	precaution and adaptation, with green and blue infrastructure to be used to handle storm water (project not yet implemented)	concept discussion

Background literature

Approaches to experiment evaluation

Several approaches have been suggested to define the success of experiments in the context of sustainability science. All these approaches agree in that an experiment always includes an intervention and produces empirical evidence that can be used to judge about its success. Luederitz et al. (2017, p. 64) present an evaluation scheme that "appraise[s] the extent to which a sustainability transition experiment generates desired effects, and how this was accomplished". They suggest focusing on the outputs and outcomes of an experiment. The possible outputs are "built capacities, actionable knowledge, accountability, structural changes", and facilitation in the "up-take of experiments" (p. 65). The possible outcomes are "socio-ecological integrity, livelihood sufficiency and opportunity, intra- and intergenerational equity, resource maintenance and efficiency, socio-ecological stewardship and democratic governance", as well as "precaution and adaptation" (p. 65). Kivimaa et al. (2017, p. 21) also focus on outputs and outcomes, but define them separately for each of seven types of change that the reviewed experiments generate: changed discourse, policy and institutional change, changed consumer or citizen practices, new technology, built environment and infrastructure change, new business practices, and new markets or market change.

Van den Heiligenberg et al. (2017) let their interviewees define success in their experiment, but focus on a long-term understanding of success in terms of whether the experiment contributes to upscaling and a regime change. Caniglia et al. (2017, p. 41) focus on the evidence that experiments generate about either the complex causal dynamics underpinning sustainability problems, or the effectiveness of tested solutions for sustainability problems. The solutions, for example, are produced in living labs, real-world labs, transition labs, and niche experiments (p. 43). More recently, Williams and Robinson (2020, p. 59) proposed a three-way evaluation framework that examines experiments via processes, societal effects, and sustainability transitions impacts. Kampfmann et al. (2023, p. 137) additionally distinguish between a narrow (internal aspects are in the foreground) and a broad (looking beyond the respective case) evaluation approach.

However, these reviews remain largely silent about the ways in which the respective evidence about outputs, outcomes, and impacts from individual studies was interpreted. The basis for including specific experiment reports into this study as illustrations for successful achievement of certain outputs or outcomes is found in the statements about such success given in the reviewed articles. In the following, I re-examine these statements from the point of view of process and variance theory with the purpose of identifying the characteristic attributes of both types of causal inference.

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Types of causal inference

The calls to evaluate the success or effectiveness of experiments in increasing sustainability (e. g., Williams and Robinson 2020) are motivated by the need to know and be able to explain how societies can be transformed, which interventions work, and which do not. The quest to explain actual effects of a particular phenomenon is what also constitutes the key objective of social scientific research, the methods of which allow distinguishing between competing claims (Sorrell 2018). Here, often a distinction is made between two approaches or theories to explaining why certain things happen: the variance approach and the process approach (Abell 2004, Geels 2011, Sorrell 2018).

In the *variance approach,* the conclusion that A influences B is derived from an experimental or quasi-experimental setting where A can be manipulated individually and different situations can be compared. This ideal image is derived from the natural sciences, and in general it cannot be achieved when studying social phenomena. In practice, statistical methods are often applied to establish a correlation between the presumed explanatory variable (the cause) and the dependent variable (the effect) (Morris 2005, Sorrell 2018).

In the *process approach,* the focus is on explaining a sequence of events, where the causes are usually multiple and intertwined. It is therefore not possible to control the causal variable(s) during an intervention. Hypotheses about the suspected chain of events that connect A and B are thus formulated and an explanation of the events aims to show "beyond a reasonable doubt" that different causes are accounted for, as either present or absent. This is often referred to as a narrative-type explanation. Characteristic of such causal inference is the definition of critical events or distinctive markers that are connected to certain causes and can help make statements about the process connecting the events (Morris 2005, Sorrell 2018).

Both approaches have their strengths and weaknesses, and various scientific disciplines view them differently. In medicine, for example, evidence from randomized and controlled trials (variance approach) is strongly preferred to evidence from case reports (process approach) (Caniglia et al. 2017). In sustainability transitions literature, however, variance-based methods are considered to have limited usefulness and narrative-type explanations are preferred (Geels 2011). In this paper, I acknowledge that both approaches have their empirical merits and my aim is to identify the features of these approaches in the experiment reports documenting how an intervention leads to "success". My expectation is that the process approach is used more frequently, due to the type of the literature I am looking at. I follow the researchers that use the term "experiment" in a broad sense (Ansell and Bartenberger 2016), which allows using it to describe analysed interventions that apply both variance and process theory.

Review of explanatory approaches in the experiment reports

Review methodology

For the examination of experiment reports, I take a qualitative, case-based approach (Lucas 1974) and aim at finding specific attributes of either the process or the variance approach. As the literature on real-world sustainability-oriented experimentation is very large, I limit the examination to the cases already cited as examples of successful experiments in previous reviews. To keep the task manageable, the sample of experiments under investigation is defined by the large evaluation-focused reviews included into the special issue *Experimentation for climate change solutions* in the *Journal of Cleaner Production* (Hilden et al. 2017) as

well as by a more recent review on real-world laboratories evaluation by Kampfmann et al. (2023). In particular, I build upon four cases explicitly cited as examples of "sustainability solutions" in Caniglia et al. (2017), 14 "illustrative examples" for outputs (8) and outcomes (6) of experiments cited by Luederitz et al. (2017), and four sustainability-related evaluation studies from Kampfmann et al. (2023). Due to multiple references to the Rotterdam community arena case, the total number of experiments reviewed is equal to 20. As this is not a systematic review, no statistical analysis is attempted.

Due to the way in which individual studies are cited in the original reviews, the unit of analysis in this paper is the experiment. In the studies that described several experiments, only the experiments previously cited as a (successful) illustration of an output, an outcome, or a solution are revisited. In the following, I refer to the studies in the sample as experiment reports.

Recognising and reflecting on such biases where appropriate, and adapting procedures accordingly, may strengthen the validity of the evidence produced and help other researchers in designing their experiments.

A qualitative content analysis of each experiment report was performed to identify attributes of the process and the variance approach in the description of the results of the experiments. The attributes of the variance approach contain experiment design in terms of a control group and a treatment group, a large sample for which the measurements were carried out, or the use of statistical methods to isolate the effect of a causal variable. The attributes of a process approach are the narrative-type explanation of the effects based on process observation, critical events that with little doubt can be ascribed to the intervention, or comparisons (in terms of some key indicators) to cases without an intervention. The extraction of such attributes allows then to categorize each experiment report as illustrating the process approach, the variance approach, or none of the both in the case when the report does not contain sufficient evidence.

Review results

The results of the review are documented in table 1 (pp. 90/91). In terms of (self-stated) experiment typology, the reviewed cases include living labs, transition experiments, community engagement experiments, socio-technical experiments, pilot projects, etc. (see table 1, second column), thus covering a rather broad set of real-world experimental approaches. The definitions of success (achievement of objectives) as well as the attributes of the explanatory approach (process or variance) were extracted from the full texts of the reports.

Six cases (three living labs, two pilot projects and one field experiment) are classified as reporting their evidence in a manner consistent with the variance approach (table 1, first section). In terms of a more recent classification by Bulkeley et al. (2019), the three living labs here would however be considered as belonging to a more narrow class of "trials". Four experiments are related to energy saving and two to farming practices. In all cases, the effects of the intervention are measured in terms of quantitative indicators and analysed using statistical methods. This forms the basis for the conclusions regarding the direct outcomes of the experiments and the statements about experiment success.

In ten experiment reports, the attributes of the process approach are identified (table 1, second section). This includes three transition experiments, two socio-technical experiments, one sustainability experiment, a living lab, a community engagement experiment, an education program pilot, and a study of strategic niche management. Most of them focus on some type of social innovation. The explanations of the effects of the experiments in these cases are of narrative-type, always involving the description of the process and of certain critical or distinctive events that could be attributed to the respective intervention. The examples of such critical events include increased customer satisfaction with a care service (Loorbach and Rotman 2010) or the establishment of a formalized political association for water governance (Bos and Brown 2012). In many cases, such process description is enhanced by evidence from interviews with participants or group discussions. Bos and Brown (2012) employ oral histories, semi-structured interviews, group interviews, and surveys to gather statements regarding the governance before and after the experiment, the perceived outcomes, and the learning process. Wiek and Kay (2015) employ continuous reflection and peer evaluation in order to assess a solution-oriented sustainability learning experiment. In the cases analysed by Wittmayer and Schäpke (2014) as well as the ones described by Hubeau et al. (2017) reflective monitoring interviews are conducted and evaluation meetings organised to discuss the outcomes of the experiments.

Four experiment reports in the sample are allocated to neither process nor variance approach (table 1, third section), although they include some characteristic features of the process approach. The respective experiments had not yet been finalized at the time the reports were published. Thus, the evidence on the achievement of experiment objectives can be viewed as insufficient, despite their use as illustrative cases in Luederitz et al. (2017).

The small size of the sample does not allow strong claims to be made regarding the correspondence between experiment types and chosen explanatory style. Nevertheless, the process approach seems to dominate the sample, with the variance approach be- >

ing applied in several reports on (trial) living labs, field experiments, and pilots. Characteristic of the latter is the focus on technology (in contrast to governance or learning) in the conducted experiments.

Dealing with caveats in the evaluation methods and the data

An important observation made while reviewing experiment reports is the limited acknowledgement of and critical reflection on possible limitations associated with the methods used or the data collected. This is in stark contrast to the usual practice in reporting the results of real-world experiments in other fields (e. g., List and Price 2016), where a lot of attention is devoted to discussing possible sources of error in the explanatory approach.

Hubeau et al. (2017) provide an example of a comprehensive experiment evaluation procedure, and state that the participatory evaluation approach was very time consuming. Regarding quantitative methods, only Adkins et al. (2010) and Baedeker et al. (2014) mention measurement errors. These are relevant in experiment settings involving sensors or digital tools that are used by the participants.

Only Plaisier et al. (2019) and Ceschin (2014) explicitly acknowledge the limitations in their sampling methodology. The process of selecting participants or evaluators in the experiments is however very important. Much of the literature on sustainability transformations emphasises the importance of "frontrunners" or "pioneers of change", the most active individuals from different domains that try to advance transformation towards sustainability in their working places or their neighbourhoods (Loorbach and Rotmans 2010). The design of many experiments, especially those involving transition arenas (e. g., Wittmayer and Schäpke 2014), purposefully addresses exactly such individuals to participate in developing alternative pathways and visions for the future. However, as Mock et al. (2019) report, the procedures typically used to select such individuals, for example snowball sampling, limit control over diversity or representativeness of the sample. This can be called sample selection bias. This bias restricts the possibility to generalize or transfer the results of the experiment. It is thus relevant in the context of experiments focusing on deepening, broadening, and upscaling strategies. Gebhardt and König (2021, p. 337), for example, advise against "cherry picking" and suggest ways to broaden participation in real-world laboratories.

It is important that authors of experiment reports think critically about the presence of these and other sources of bias and take steps to correct them. This would strengthen the scientific rigour of the evidence produced and help other researchers in the design of their experiments.

Conclusions

This paper revisits a number of studies that were previously cited as examples of successful sustainability-oriented real-world experiments with the aim of uncovering the logic and methods used to demonstrate experiment success. Based on a distinction often made in the social sciences and employing qualitative content analysis, I look for attributes of either the variance or the process approach to causal inference in the respective studies. I find that reports on transition governance experiments, socio-technical experiments, and community-based interventions display attributes of the process approach. Technology-focused trials, pilots, and field experiments, in contrast, use quantitative methods consistent with the variance approach. The process approach is employed more widely in the sample. Some studies do not provide sufficient evidence for their success in achieving the stated objectives.

An important observation in the reviewed cases is the limited reflection on possible caveats connected to the employed methods or the data. I discuss several sources of biases that can be of relevance in the context of sustainability-oriented real-world experiments. Typical mistakes here are related to measurement or participant selection. Recognising and reflecting on such biases where appropriate, and adapting procedures accordingly, may strengthen the validity of the evidence produced and help other researchers in designing their experiments.

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