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Leverage points for sustainability transformation: a review on interventions in food and energy systems

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ABSTRACT

There is increasing recognition that sustainability science should be solutions orientated and that such solutions will often require transformative change. However, the concrete sustainability interventions are often not clearly communicated, especially when it comes to the transformative change being created. Using food and energy systems as illustrative examples we performed a quantitative systematic review of empirical research addressing sustainability interventions. We use a modified version of Donella Meadows' notion of 'leverage points' – places in complex systems where relatively small changes can lead to potentially transformative systemic changes – to classify different interventions according to their potential for system wide change and sustainability transformation. Our results indicate that the type of interventions studied in the literature are partially driven by research methods and problem framings and that 'deep leverage points' related to changing the system's rules, values and paradigms are rarely addressed. We propose that for initiating system wide transformative change, deep leverage points – the goals of a system, its intent, and rules – need to be addressed more directly. This, in turn, requires an explicit consideration of how scientific approaches shape and constrain our understanding of where we can intervene in complex systems.

1. Introduction

In the face of multiple global sustainability crises (Hoekstra and Wiedmann 2014; Steffen et al. 2018, 2015) there are increasing calls for sustainability transformation (Elmqvist et al. 2019; Kallis and March 2015; Lucas and Horton 2019) and increasing recognition that sustainability science needs to shift from a problem to solutions orientation (Komiyama and Takeuchi 2006; Miller et al. 2014; Washington 2015). While the sustainability agenda entered the academic and political arena in the 1980s (Clark and Dickson 2003; Kates 2015), the transformation towards sustainability remains, seemingly, a distant prospect. Unsolved severe sustainability issues include climate change, biodiversity loss, the exhaustion of non-renewables, and social-ecological and economic inequalities (Dorninger and Hornborg 2015; FAO 2019; Pachauri et al. 2014; Torres et al. 2017). One contributing factor to the lack of progress towards sustainability may be the way in which sustainability interventions – defined as deliberate human actions targeting sustainability in a given system of interest – are identified and studied. It has been argued that most scientific attention has been given to 'shallow' interventions that are rather simple to envision, but have a limited potential for triggering systemic change (Abson et al. 2017; Fischer et al. 2007). Those include popular efforts to increase efficiency ratios and the general focus on optimizing numbers and parameters. In isolation such interventions are not likely to achieve transformation and system wide change as long as other system characteristics remain unchanged. For example, in the case of efficiency, the 're-bound' effect prevents efforts solely focussed on efficiency gains to yield in an absolute decoupling of resource use from human activities (Alcott 2005; Zoellick and Bisht 2018). Such 'shallow'

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interventions stand in contrast to less tangible interventions, which address the underpinning, ultimate drivers of current trajectories, such as the conviction in the benefits of endless growth (Meadows 1999). Yet, such potentially more powerful interventions that address 'deeper' systems properties, and which are the underpinning, ultimate drivers of current trajectories, are under researched.

In this article we adopt a 'leverage points perspective' to review sustainability interventions in food and energy systems in order to understand which types of interventions are most often in focus and the potential of these interventions to achieve transformative change. We here define 'transformative change' of systems as a radical alteration of systemic interconnections and systems behaviour with fundamentally different sustainability outcomes. A sustainability transformation genuinely disrupts previous pathway dependencies and entails large scale non-linear shifts for more desirable social-ecological system states (Blythe et al. 2018; Hölscher et al. 2018).

In this regard, it has been argued that sustainability related literature is largely focused on symptoms treating of very specific adverse outcomes, but generally fails to address root causes of unsustainable systems behaviour (Ehrenfeld 2004). We hypothesize that this may, at least in part, be related to (1) the type of system studied and how it is bounded, (2) to the way in which researchers frame sustainability challenges, and (3) the scientific approaches they use to study possible interventions to address the identified problems. Consequently, we relate the interventions to the problem framing, scientific disciplines, and scientific methods employed in empirical research on sustainability interventions. We also explore if the investigated intervention, and its corresponding leverage point, is proposed to have transformative potential – and if so, which tool or actor is described to possess this potential? Finally, we are interested in the implementation of the intervention: who is the intervener and what is the outcome?

The leverage points concept was introduced by Donella Meadows (1999) and developed further by Abson et al. (2017). A leverage point is a point of intervention in a system of interest to alter its behaviour, trajectories, and outcomes. Meadows defined a leverage point as "a place in the system where a small change could lead to a large shift in behaviour (Meadows, 2008: 145)" She suggested a hierarchy of 12 intervention points ranging from relatively ineffective intervention points with limited transformational potential to more effective places to intervene which entail higher systemic resistance to changing it (Meadows 1999). Abson et al. (2017) synthesized Meadows' original 12 leverage points into four broad system characteristics on which sustainability interventions can be focused: systems parameters, systems feedbacks, system design, and system intent. System parameters are understood as a system's mechanistic characters (taxes, standards) and physical structure (buffers, flows). System feedbacks are the interconnections between the elements of the system which steer reinforcing (positive) or dampening (negative) feedback loops. A system's design is made of the structure of information flows, its rules, and power characteristics. Finally, the system intent is concerned with the goal of the system and with the paradigm or mindset out of which it arises (Abson et al. 2017). The four system characteristics are ranked from shallow to deep and each capture three of Meadows' original leverage points (Fig. 1). The leverage point concept provides a conceptual tool and epistemological lens through which diverging sustainability problem framings, derived interventions, and resulting outcomes can be analysed. The scale represents a hierarchy of intervention points for leveraging change in systems (Abson et al. 2017).

We focus on interventions in food and energy systems as two types of social-ecological systems that are crucial for global sustainability (GEA 2012; Godfray et al. 2010), currently on relatively unsustainable pathways (Dangerman and Schellnhuber 2013; Lucas and Horton 2019), and have received substantive research attention in the academic literature (Fig. 8 in the Appendix shows the temporal development of studies included in this review). Using two different types of social-ecological systems is intended to shed additional light on how the

Meadows (1999) Places to intervene in a System (in increasing order of effectiveness)	**Abson et al. (2017) System characteristics (nested hierarchy – increasingly constraining order)**
12. Constants, parameters, numbers (such as subsidies, taxes, standards)	
11. The sizes of buffers and other stabilizing stocks, relative to their flows	***parameters***
10. The structure of material stocks and flows (such as transport networks, population age structures)	
9. The lengths of delays, relative to the rate of system change	
8. The strength of negative feedback loops, relative to the impacts they are trying to correct against	***feedback***
7. The gain around driving positive feedback loops	
6. The structure of information flows (who does and does not have access to what kinds of information)	
5. The rules of the system (such as incentives, punishments, constraints)	***design***
4. The power to add, change, evolve, or self-organize system structure	
3. The goals of the system	
2. The mindset or paradigm out of which the system – its goals, structure, rules, delays, parameters – arises	***intent***
1. The power to transcend paradigms	

Fig. 1. The leverage points 12- and 4- scale. On the left the 12 leverage points by Meadows (1999a) in their hierarchical scale from shallow (top) to deep (bottom), and on the right the synthesized version of Abson et al. (2017) as four broad system characteristics.

'systems of interest' – the subjective delineation of boundaries and characteristics of a system based on the interests and preanalytic assumptions of the researcher (Costanza 2001; Ison 2008) — may shape understandings of transformative change. As we are interested in empirically observable interventions in real-world systems that have already been carried out or proposed to be implemented based on empirical observations, we chose to work with sustainability-focused, empirical research only.

We conduct this quantitative systematic review to provide a broad

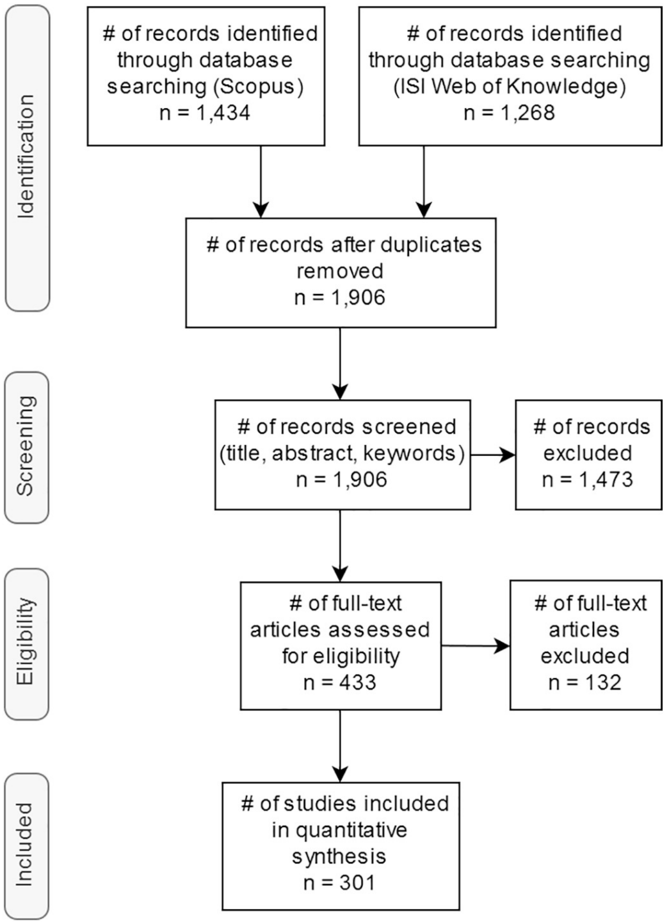

Fig. 2. Systematic case selection process as PRISMA flow diagram (Moher et al. 2009).

overview of the relevant scientific literature dealing with sustainability interventions in food and energy systems. The aim is to understand whether there are specific patterns, key thematic priorities, or blind spots in relation to the types and 'depth' of the interventions considered in the field. Sustainability science is a solution-oriented concern (Komiyama and Takeuchi 2006; Miller et al. 2014; Washington 2015) and there is a pressing need to better understand what sorts of interventions are being studied and to explore the potential of those interventions to shift key systems to sustainable pathways.

2. Method

Our systematic quantitative review follows the guidelines for the "Preferred reporting items for systematic reviews and meta-analyses" (PRISMA) framework as described by Moher et al. (2009). We developed a search string which we applied to academic literature databases to identify potentially relevant articles. We then screened the abstracts according to our inclusion criteria, applied a full-text analysis for final eligibility, and applied a coding scheme to the remaining articles to be included, which finally provided us with a set of variables for statistical analysis (Fig. 2).

On 30 October 2017 we applied our search string (see Appendix) to the databases of Scopus (www.scopus.com) and the ISI Web of Science (www.webofknowledge.com). Our search string includes publications from 1990 to 2017. One single publication was captured by the databases as to be published only in 2018. The search string was restricted to empirical academic English articles that include the term "food system "or "energy system", plus "sustainability" or "sustainable" and a term of 'change' or 'intervention' in their title, abstract or keywords. After removing duplicates, the search string yielded in a total result of 1906 articles.

We screened the title, abstract and keywords of these 1906 papers based on specific inclusion and exclusion criteria respectively: We specifically looked for empirical papers that research and report on an explicit intervention that targets sustainability change in the respective food or energy system of interest or that formulates possible interventions based on the empirical observation. Thus, the papers to be included had to describe a specific and intentional human intervention targeting sustainability in the system, either analysed or proposed based on the empirical observation. Purely descriptive or evaluative empirical studies without any intervention proposed or described were excluded from the review.

After the abstract, title, and keywords screening, we downloaded 433 papers and once again applied our inclusion and exclusion criteria, this time via a full-text eligibility assessment, resulting in 301 articles included in the review (the full list of included articles is provided in the Appendix). The coding scheme used in the systematic review was tested and refined on 12 randomly selected papers before being applied to the 301 reviewed articles. We compared the results of each reviewer to refine the coding scheme and to improve common understandings to ensure the inter-coder-reliability. The latter was additionally secured by continuous and final cross-checking the results between different reviewers for consistency in the application of the coding scheme. We coded for 16 variables – each representing one question that was applied to the reviewed articles – that can be summarized into seven groups of variables (see Table 1).

Most variables were coded in terms of exhaustive and mutually exclusive categories (variables number 1, 3, 4, 7, 8, 10, 13, 14, 15, and 16). However, for some variables multiple possible categories applied (2, 5, 6, 9, 11, and 12).[2] For example, the problem framing of a paper could include multiple dimensions (i.e., it could be framed as an economic, technical, and ecological problem). Most importantly, a particular intervention could relate to multiple leverage points (on both the 12 point leverage point scale and the four system characteristics scale) which resulted in multiple possible entries per intervention. Table 4 in the Appendix provides details of all variables and categories including how often each variable was coded for in the articles.

After coding we applied mostly descriptive analysis of the resulting variables. Subsequently, we conducted an agglomerative hierarchical cluster analysis (Ward's hierarchical cluster) to identify groups of papers that are similar in regards to their overall scientific approach (i.e., similar in their disciplinary approach, methods, problem framing, focal issue etc.). It is important to note that we excluded the intervention variables (leverage points 12-scale and 4-scale) from the cluster analysis, because we aimed to understand whether certain scientific approaches are significantly related to the type of leverage point associated with the intervention investigated. We used a hierarchical cluster analysis (Ward) with the hclust function and the agnes function (agglomerative nesting) in R (R Core Team 2018) to identify groups in our dataset where the cluster criteria follow pairwise distance matrix observations. This approach is suitable for our large dataset to identify groups in the data according to dissimilarity (minimum within-cluster variance). The Ward's hierarchical clustering does not require pre-specified number of clusters (Ward 1963). To identify which variables characterize the resulting clusters we used the indval function of the labdsv package in R.

We used the resulting cluster groups and other significant variables to create a flow chart and barplots to analyse the connections of variables to one another (e.g. which problem framing is more or less strongly connected to a specific leverage point). Lastly, we analysed correlations (Chi^2 tests of independence) between the leverage point(s)

[2] Note that the allowance of multiple entries also affects the proportions within the variable (compare Fig. 3 below and Table 4 in the appendix), i.e. each entry counts separately and one single paper can have multiple entries which affects the proportion within the variable.

Table 1
The 16 variables of the coding scheme grouped in seven categories.

1. System 1. System (food or energy) 2. System aspect 3. Spatial scale	4. Scientific problem 9. Problem framing 10. Focal issue	7. Implementation 15. Primary intervener/executer 16. Outcome of the intervention
2. Method 4. Datatype 5. Analysis 6. Evaluation	**5. Intervention** 11. Leverage point 4-scale (Abson et al., 2017) 12. Leverage point 12-scale (Meadows, 1999)	
3. Discipline 7. Principal discipline 8. Disciplinary approach (single-, inter-, or transdisciplinary)	**6. Transformation** 13. Transformative potential (yes or no) 14. Transformative tool	

and the cluster, problem framing, or stated outcome of the intervention. All analyses were carried out in R (R Core Team 2018).

3. Results

3.1. Overview

Out of the 301 articles included in this review 129 papers were concerned with food systems and 172 with energy systems (Fig. 3).[3] The system aspects studied were mostly energy generation (23%), consumption of food or energy (18%), general system structure (17%) and the production of food (16%). Supply and transportation (14%) as well as emissions (6%) were studied to a lesser extent. Regarding the spatial scale of the system investigated, we found strong representations of national (31%), local (26%), and regional (21%) studies. Systems on the lab scale (10%) or on the global scale (6%) were studied less often (Fig. 3).

Studies used mostly quantitative data (49%), some qualitative (23%), and fewer mixed data (21%). The methods of data analysis were mostly statistics (24%) and modelling (17%), but also qualitative (23%) and content (12%) analysis. The data were often evaluated via a monitoring of flows (26%), a technical performance analysis (19%), with institutional (13%) and behavioural change (13%) evaluation, or with a cost-benefit analysis (12%) (Fig. 3).

The key disciplines for the intervention were (in decreasing order of magnitude): policy (food or energy policy) (30%), engineering (28%), social-ecological studies (20%), sociology (14%), economics (5%), and physics and chemistry (4%). For the disciplinary approach we differed between single disciplinary approach (63%), interdisciplinary studies (29%), and transdisciplinary approaches (8%) (Fig. 3).

The problem framing on the reviewed articles was relatively balanced between social (27%), technological (23%), economic (19%), ecological (16%), and/or political (13%) framings. The focal issue was often described as emissions (31%), followed by natural resource degradation (19%), food insecurity (15%) and inefficiency (12%). The lack of knowledge (10%) and inequality and power (8%) were less often focused on.

The application of the leverage point 4- scale (based on Abson et al. 2017), revealed that 41% of the reviewed papers studied interventions on the system's parameter characteristics, 17% were concerned with feedbacks, 37% with the design characterises of the system, and 5% with the system's intent (note that multiple entries were possible for this variable). The use of the leverage point 12-scale (from Meadows 1999) opens up the four system characteristics into more specific intervention points. Note that the proportional divergence compared to the leverage point 4-scale is due to the possibility of multiple classifications in either scale.

[3] A temporal development of publication numbers split by food and energy is included in the appendix (Fig. 8).

The majority of interventions were not explicitly described as to be of transformative character (80%). Of the remaining fifth, 27% envision transformation by a new technology, 20% by new energy carriers, 15% by new laws and policy, 12% via justice and power redistribution, 10% via education and learning, and 10% by implementing organic production.

The primary interveners were described to be policy makers (44%), followed by engineers (15%) and scientists (14%). 24% of the interventions were to be undertaken by local communities, cooperatives, and farmers. The outcome of the intervention was described to be either more efficient technology (30%), food or energy security (22%), lower emissions (18%), more knowledge (16%), more collaboration (6%) or a shift in norms and paradigms (5%).

3.2. Clustering scientific approaches

The cluster analysis resulted in four clusters (agglomerative coefficient of 0.87), each representing one scientific approach (Fig. 4). Based on results of the analysis of the defining variables for each cluster group (Table 3) we labelled the clusters accordingly:

1. The ‘engineering’ cluster ($n = 52$) was characterized by a focus on energy generation in labs, using mathematical equations and technical performance analysis, by engineering approaches, a technological problem framing around inefficiencies, a transformative potential via new energy carriers, and engineering interventions targeting efficient technology and flows.
2. The ‘technocratic’ cluster ($n = 125$) focused on the national energy policy, a political problem framing, a focus on emissions, and policy makers as primary interveners.
3. The ‘sociopolitical’ cluster ($n = 88$) featured a focus on local systems, a mixed and qualitative data analysis and evaluation of changed behaviours, with a social problem framing, a focus on food insecurity and health, organic production as proposed to have transformative potential, local communities as primary executers of the intervention, and an envisioned outcome of higher food security.
4. The ‘social-ecological’ cluster ($n = 36$) featured a particular focus on global food production, a quantitative analysis of flow indicators, operates from an interdisciplinary social-ecological perspective, applies an ecological problem framing on natural resource degradation, does not explicitly suggest to be of transformative character, and is mostly implemented by spatial and urban planners.

The right-hand part of Fig. 4 shows the rapid increase over time in literature addressing sustainability interventions in food and energy systems. While there was some kind of general take off in 2015, it is hard to judge if any specific approach gained more importance than others over time. The proportions of the 4 clusters seem to develop rather proportionally.

As described above, Table 2 provides details about how strongly which variables (coefficients in parenthesis) define a cluster and

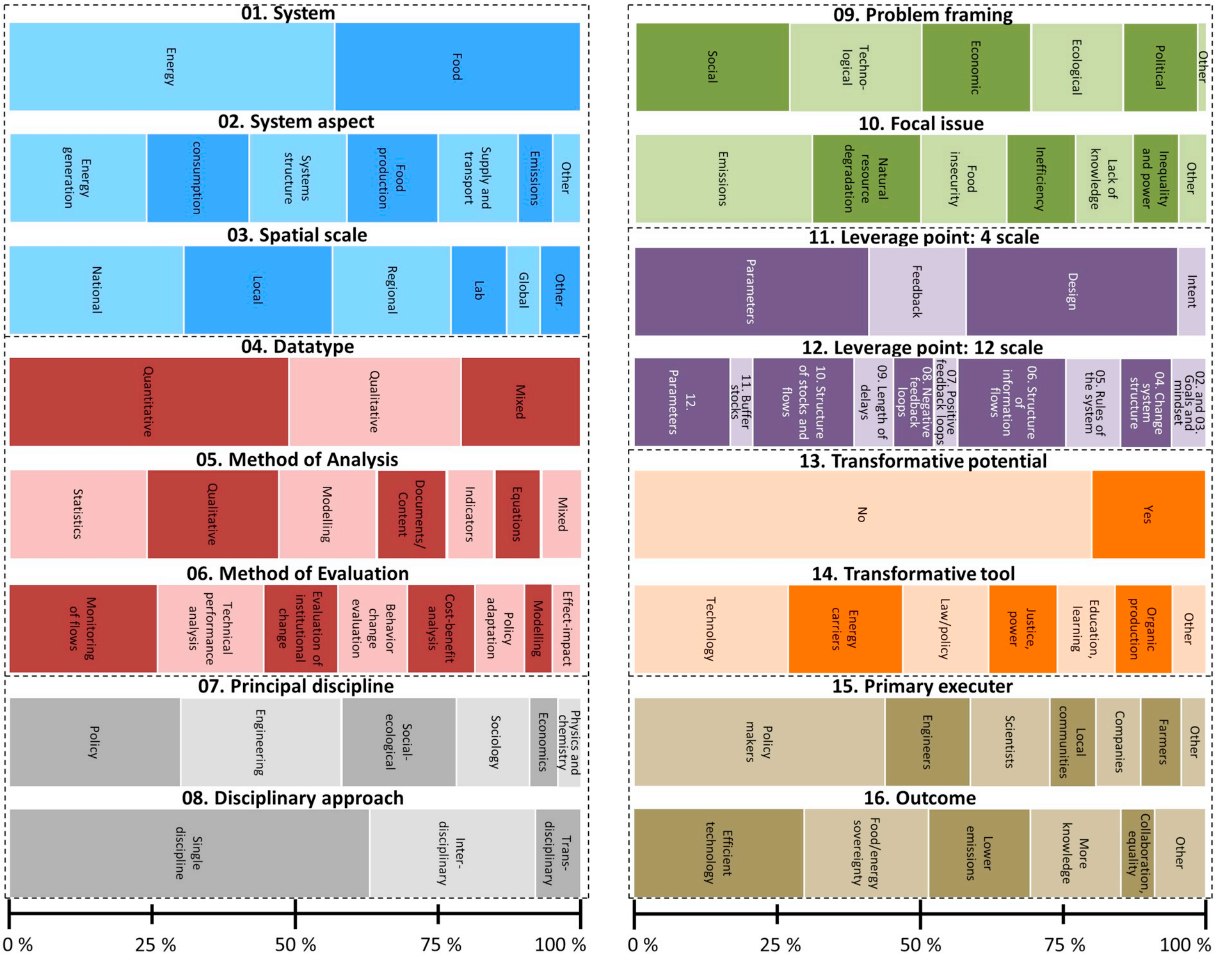

Fig. 3. The proportions of all categories within their variable. Each group of variables is indicated with same shades of colour and with a dotted box. The stacked barplots present the results of both food and energy system papers combined.

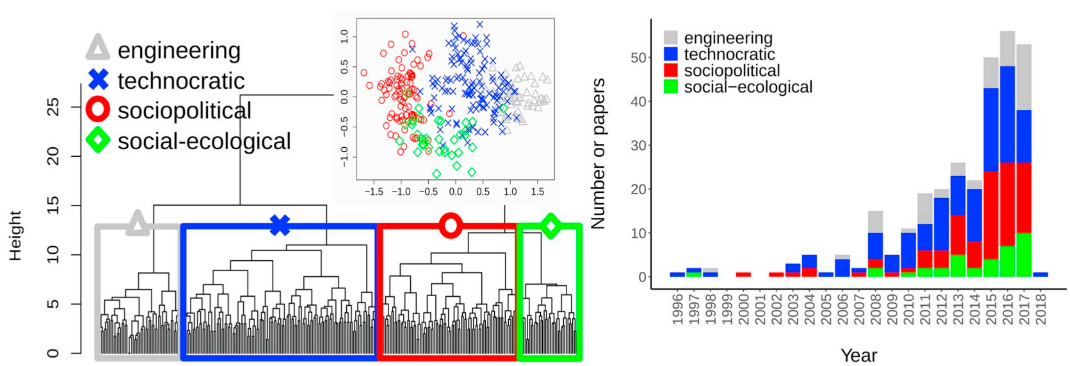

Fig. 4. Results of the cluster analysis visualized in a dendrogram and an ordination (left), and the temporal development of the clusters as in papers included in the review (right).

differentiate one cluster from the others. For example, the engineering cluster is distinguished from other clusters by its high prevalence of articles studying energy systems, energy generation, and the lab scale. However, there is no specific datatype that was dominating in these studies.

3.3. Connectivity within scientific approaches

We used a Sankey diagram (Fig. 5) to illustrate the connections between the different variable categories, including the modelled variable of the 'scientific approach'. Technocratic and engineering approaches almost exclusively prevailed in the scientific literature on energy systems. The literature on food systems were mostly based on a social-ecological or sociopolitical approach.

The scientific approaches were strongly related to the problem framing. Engineering approaches implied either an economic or technological problem framing. The technocratic approach was relatively evenly spread among the entire possible problem framing categories. Sociopolitical approaches had a strong tendency framing their research problem as social, political, or economic. And the social-ecological studies most often came with an ecological, social, or economic problem framing.

Table 2
Results of the cluster analysis and the cluster's determining variables. The value in parenthesis indicates the strength of the coefficient in distinguishing the cluster from others. Note that the variable group on interventions (no. 5 – leverage points) are not included in the cluster analysis. All coefficients are shown, but not more than one for each variable category, only the strongest one. All coefficients shown are significant at $p < 0.05$.

Variable	*Scientific approach*			
	Engineering (n = 52)	Technocratic (n = 125)	Sociopolitical (n = 88)	Social-ecological (n = 36)
(1) System	Energy (0.51)	-	-	Food (0.49)
System aspect	Energy generation (0.38)	-	-	Food production (0.30)
Spatial scale	Lab (0.44)	National (0.22)	Local (0.19)	Global (0.09)
(2) Methods				
Datatype	-	-	Mixed (0.30)	Quantitative (0.37)
Analysis	Mathematical equations (0.20)	-	Qualitative analysis (0.29)	Indicators (0.12)
Evaluation	Technical performance analysis (0.25)	-	Behaviour change evaluation (0.09)	Monitoring of flows (0.24)
(3) Discipline				
Principal discipline	Engineering (0.40)	Policy energy (0.37)	Sociology (0.26)	Social-ecological (0.34)
Disciplinary approach	Single disciplinary approach (0.36)	-	Transdisciplinary (0.11)	Interdisciplinary (0.25)
(4) Scientific Problem				
Problem framing	Technological (0.57)	Political (0.12)	Social (0.34)	Ecological (0.26)
Focal issue	Inefficiency (0.26)	Emissions (0.26)	Food insecurity and health (0.24)	Natural degradation (0.25)
(6) Transformation				
Transformative potential	Energy carriers (0.08)	-	Organic production (0.07)	No (0.29)
(7) Implementation				
Primary executers	Engineers (0.65)	Policy makers (0.27)	Local communities (0.14)	Urban/spatial planners (0.07)
Outcome	Efficient technology and flows (0.33)	-	Food security (0.29)	-

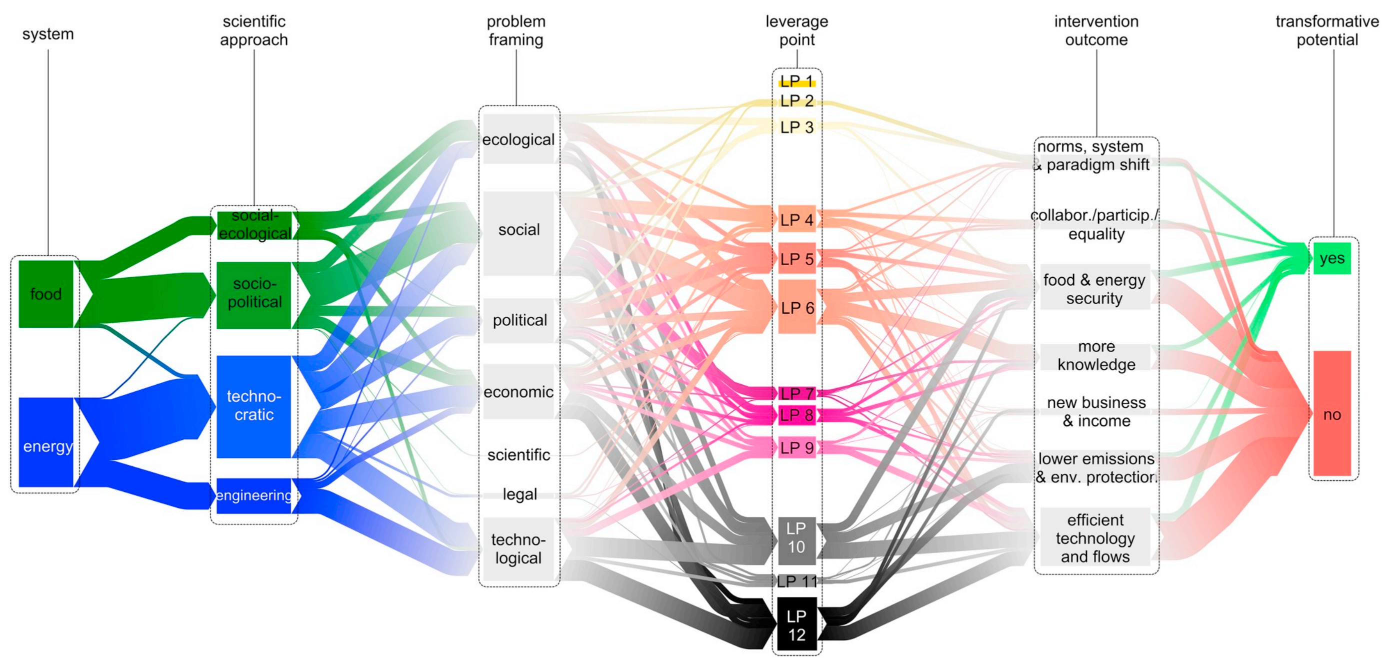

Fig. 5. Sankey diagram showing connections between variables and categories. Colours were selected for ease of visualization. Due to the multiple possible categories in the variables 'problem framing' and 'leverage point', there is an imbalance in in- and outflows for various variable categories.

The interventions concerned with system parameters (leverage points 10–12) often had a technological or economic problem framing. The feedback system characteristics (leverage points 7–9) were frequently related to social or technological problem framings. The design related interventions (leverage points 4–6) were primarily rooted in an ecological, social, or political problem framing. And lastly, the deepest, intent related, system characteristics (Leverage points 1–3) were rarely addressed, but evolved out of multiple problem framings.

The four outcomes most often ascribed to the single interventions (in decreasing order) were efficient technology and flows, food and energy security, more knowledge, and lower emissions and environmental protection. Deeper system properties, like norms and equality, were less often targeted by the interventions. The self-attribution of transformative potential was relatively evenly distributed among the possible intervention outcomes. Nevertheless, the majority of cases do not explicitly link their research to sustainability transformation.

3.4. The leverage potential of interventions

In the following, we relate the scientific approach, problem framing and outcome to the 'depth' of intervention (i.e. which system characteristics were being intervened in, see Fig. 6). The engineering approach largely targeted system parameters. The technocratic approach very rarely involved interventions on system intent, but addressed parameter, feedback, and design type of interventions in relatively equal proportions. In contrast, the sociopolitical approach features a noticeable focus on system intent and system design. The social-ecological approach exhibited the most balanced proportion of system interventions, including the most pronounced focus on system feedbacks and a considerable share of interventions challenging the intent of the

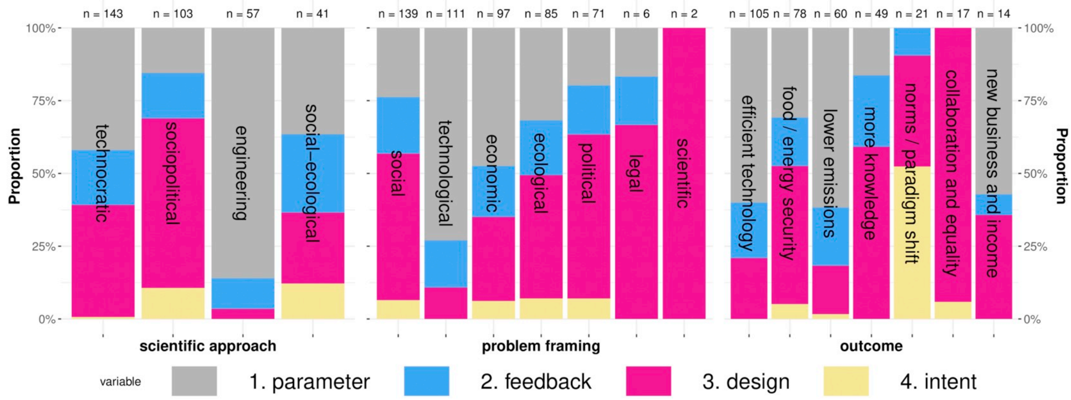

Fig. 6. Stacked bar plots showing the distribution of leverage points within variable categories. The categories of three variables (scientific approach, problem framing, and outcome) are contrasted with the associated system characteristics being intervened on (parameters, feedback, design and intent).

system (Fig. 6).

Our analysis showed that the leverage points approached varied according to the problem framing applied. While the framing of a sustainability problem as a social, ecological, political or economic problem results in a relatively larger share of system intent and system design related interventions, the technological problem framing yielded mostly interventions targeting the system parameters. An economic, ecological, or political problem framing involves similar leverage points as the social problem framing, with partially stronger emphases on system parameter interventions.

With regards to the interventions' proposed (or observed) outcomes, efficient technology, lower emissions, and new business and income largely stemmed from interventions on the system's parameter level. Interventions concerned with feedbacks, design, or the system intent much less often resulted in efficient technology, lower emissions or new business and income. For outcomes related to norms and paradigm shift more than half of the interventions targeted system intent. Outcomes that resulted in more collaboration and equality were largely related to interventions in system design (system goals, rules, flow of information).

For each Chi^2 test (scientific approach vs. leverage point; problem framing vs. leverage point; outcome vs. leverage point) we found a highly significant relation ($p < 0.01$) indicating statistical non-independence (see Fig. 7 below and Tables 5, 6, and 7 in the Appendix and for detailed results of the tests, including the observed, expected, and residual values). Fig. 7 reveals that sociopolitical approaches had a significantly stronger than average focus on deeper leverage points (design and intent interventions) but miss parameter type of interventions. System parameters were much more abundant in the engineering approach. In comparison to the total average over all four approaches, the social-ecological approach lacks design type of interventions but is overrepresented regarding interventions on system feedback and system intent. Technological problem framings are more abundant in shallow leverage points, i.e. parameters, and significantly less abundant in applying deeper leverage points (design and intent). Social and political problem framings involve an emphasis on design and intent characteristics of a system, but lack parameter type of interventions.

4. Discussion

There is a wide variety of different research investigating interventions that target sustainability in food and energy systems, ranging from qualitative in-depth interview studies on the personal values of individual actors (e.g., Lautenschlager and Smith 2007) to quantitative assessments of the steel industry to reduce GHG emissions with hydrogen as an auxiliary reducing agent in the blast furnace (e.g., Yilmaz et al. 2017). A leverage points lens provides a common heuristic framework for classifying these diverse interventions in relation to the broad system characteristics that the interventions address.

Within the empirical literature on sustainability interventions in food and energy issues, there was a strong focus on intervening in the more tangible and relatively easy to conceive system parameters (taxes, incentives, flows of physical inputs etc.) – with a similar level of focus on intervening in the system design (structure of information flows, rules, power structures etc.) that shape the management of these institutions. However, the largest fraction of design type of interventions stemmed from new forms of knowledge production (coded as leverage points 6: structure of information flows) – which is an almost natural response of science to suggest the creation of more knowledge. We reason that this strong emphasis on information flow is almost a natural bias in science. As academic research is very self-reflective and focused on the production of new knowledge the gravitation towards this leverage point is no coincidence. It is likely that scientists focus on the idea that knowledge needs to be shared and that we need greater understandings of systems, how systems work, and how we can do better research.

However, sustainability transformation requires not only more knowledge but different values (Chan et al. 2016; Horcea-Milcu et al. 2019; Kohler et al. 2019). Yet, there was considerably less emphasis on

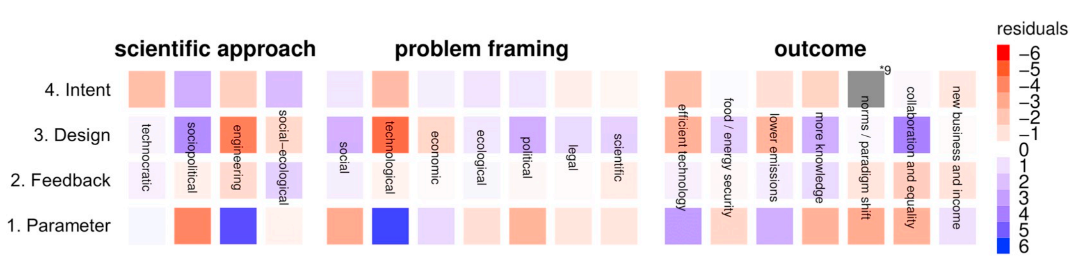

Fig. 7. Coloured rectangles representing the residuals of Chi^2 tests. Red rectangles indicate negative residuals (underrepresentation) and blue rectangles positive residual values (overrepresentation) compared to the average. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

interventions related to shortening or strengthening feedback loops within these systems, like the reconnection of human activities to natural cycles (Dorninger et al. 2017; Ives et al. 2018), and even less focus on attempts to intervene in the underpinning values, worldviews and paradigms that ultimately shape those systems (see Fig. 3). This despite the fact that, particularly for a normative research agenda like sustainability (Schmieg et al. 2018), the intent characteristics of a system, i.e. the goal of the system and the paradigm out of which a system arises, are of crucial importance (Fischer and Riechers 2019; Gladkykh et al. 2018).

This gap in the literature matters because the four broad system characteristics can be considered as hierarchically nested and constraining (Abson et al. 2017). In other words, the system intent (the goal to which the system is oriented) shapes the physical and institutional design of the system, which in turn determines the feedback that the system provides regarding (un)sustainable functioning and therefore the type of parameter that can, or should be, adjusted to shift systems towards sustainability.

This is in no way to suggest that addressing interventions seeking to alter system parameters is not valuable. Indeed, parameter focused interventions may be vital in terms of concrete changes in system sustainability. Research investigating the parameters of a system and the concrete sustainability outcomes in terms of emissions, biodiversity indices, measures of inequality etc., are extremely valuable and, in fact, indispensable for sustainability informed policies. However, we would argue that the scope of changes to such parameters by actors through processes from within the system is constrained by 'deeper' system characteristics. Therefore, attempts to close the 'sustainability gap' – the discrepancy between sustainability targets and ability of current interventions to generate transformative change (Fischer et al. 2007) — may require changes in system intent and design for radical changes in system parameters to be enabled. This sustainability gap is also highlighted by the small number of articles which identified the interventions they studied as transformative (Fig. 5).

Similarly, sociopolitical approaches concerned with system norms and paradigms would benefit from bridging the gap to changing system parameters. For example, how does a paradigm shift play out in terms of sustainability outcomes, given that not all changes in norms and values necessarily result in favourable sustainability outcomes (see for example the environmental awareness – action gap: Kollmuss and Agyeman 2002; O'Brien 2013)?

A focus on neglected system feedbacks in relation to transformative change, particularly in the context of complex social-ecological systems (Lambin and Meyfroidt 2010), may be crucial in motivating transformative change, by shortening or strengthening feedbacks between behaviour and impacts (Dorninger et al. 2017; Sundkvist et al. 2005).In addition to a need for more focus on system feedbacks and system intent, our results suggest that there is a need for greater emphasis on the interactions between interventions on different system characteristics. We find that different scientific approaches tend to focus on specific system characteristics (for example, the field of engineering approaches on parameters and sociopolitical approaches on system design). This is perhaps unsurprising given the traditional expertise and focus of different scientific approaches, but does highlight the need for genuinely interdisciplinary approaches in sustainability science (Bammer 2013). The lack of overlap between the four broad scientific approaches (engineering, technocratic, social-ecological and sociopolitical) used to study sustainability interventions in food and energy systems (Fig. 4) can be problematic, for several reasons. Firstly, it limits opportunities for studying interactions between interventions at different leverage points (Abson et al. 2017; Meadows, 1999). Secondly, it potentially leads to policy incoherence (Grabel 2011; Peters and Savoie 1996) due to the siloed expertise associated with interventions into different system characteristics that are, in practice, tightly interdependent. Sustainability science would greatly benefit from not only interdisciplinary work, but work that integrates expertise and foci on both ends of the leverage points scale.

Moreover, we find there is a clear and significant tendency to favour specific intervention points depending on the problem framing. The difference is especially pronounced between social and technological problem framings. While we have acknowledged possible multiple problem framings for each reviewed case, i.e. a paper could have a social and technological problem framing combined, the relation to the leverage points was still significantly dependent on the problem framing. What is identified as sustainability problem will influence the range of possible interventions a study will address. The leverage points scale can be used as a conceptual tool to explore how problem framing constrains or enables the investigation or identification of interventions for changing a system's behaviour based on the 'depth' of the intervention.

We do not suggest that sustainability transformation is an end in itself or that it is an inevitable apolitical process (Blythe et al. 2018). One relevant area that this paper does not touch on is *who* is doing (or is proposed to do) the intervening for transformation. This opens up some challenging normative and ethical questions regarding transformation. While we do not have space to go into this here, it is certainly an important an area for future research.

5. Conclusion

Sustainability research that addresses interventions in complex systems needs to better understand interconnections, and feedbacks between different system characteristics. Adopting a leverage points perspective on sustainability interventions implies taking a systems perspective on how transformation might happen, where structural or ideological system properties constrain one another. System transformation can be triggered via a broad range of possible interventions, at various places in the system (i.e. the 12 leverage points, Meadows, 1999), all of which have their own contribution to make. However, our findings suggest that empirical studies on interventions at deep leverage points are scarce and that research approaches encompassing both deep and shallow leverage points are largely missing.

If the academic research community aims to play an important role in initiating system wide transformative change, deep leverage points – the goals of a system, its intent, and rules – need to be addressed much more directly. For this, scientific discourses will have to change, hence we suggest the need to shift from disciplinary focus on optimization of (sub)systems of interest, to interdisciplinary approaches spanning systems parameters, feedbacks, design, and intent.

Declaration of competing interest

The authors declare no competing interests.

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Appendix A. Supplementary data

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