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RESEARCH ARTICLE

'Chains of leverage' as way to identify and foster transformative potential

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Abstract

1. We propose the framework of 'chains of leverage'. It is an operationalisation to understand and analyse the transformative potential of social-ecological systems and identify leverage points for sustainability transformations through a concrete four-step approach.
2. *Step 1*: Analysing the social-ecological system regarding its core elements across system depth. Elements in a system can be situated at different system depths (from shallow to deep) relating to system parameters, feedbacks, designs and intents.
3. *Step 2*: Highlighting interactions and relationships between these elements across system depth; identifying if the relationship between elements can be categorised as dominant or alternative (suppressed), and if these elements are in contrast with each other; scrutinising the system for destructive elements or events.
4. *Step 3*: Linking elements to ascertain if there are (coherent) chains of leverage. We define a 'chain of leverage' as a situation within a system in which multiple elements across system depths and governance levels have synergistic impact on each other. This step assesses how one type of change in a system might precipitate further changes across different system depths. Hence, we may find sequences of how shallow, mid-level and deep system elements flow on from and reinforce one another, creating a chain of leverage, which may be in conflict with an alternative chain of leverage.
5. *Step 4*: Identifying leverage points to intervene either to (i) create a coherent chain of leverage that fosters sustainability, (ii) strengthen a currently weak element or chain that fosters sustainability, (iii) deconstruct or disempower existing, unsustainable elements or chains and (iv) eliminate or weaken disruptive elements that can negatively influence the sustainability of the system.

6. Many systems are locked in unsustainable states, and we have yet to find ways to shift onto pathways for sustainability. The framework of chains of leverage can facilitate such a shift through helping to understand a system's transformative potential and to identify a coherent set of leverage points for sustainability transformation.

KEYWORDS
SDGs, social-ecological systems, sustainability management, transformative change, transition, visions

1 | THE NEED TO IDENTIFY TRANSFORMATIVE POTENTIAL

Despite global efforts, the current trajectory of our planet is unsustainable (Richardson et al., 2023; Rockström et al., 2023)—making it necessary to focus on sustainability transformations of Earth's social-ecological systems (Folke et al., 2020). Sustainability transformation entails systemic changes that fundamentally shift system functionality and outcomes, resulting in the emergence of a new system or a new regime (Backstrom et al., 2018; Graham et al., 2014). Such fundamental transformation can be related to changes in the design and intent of the system (e.g. structures and functions) as well as in their relational aspects (such as system feedbacks) towards a more just and equitable world (O'Brien, 2018; Patterson et al., 2017).

Sustainability transformation has been hindered by the difficulty to identify and foster the transformative potential of social-ecological systems, as the capacity to recognise places to intervene where a small shift can produce systemic change (i.e. leverage points, see Meadows, 1999) is limited. 'Transformative potential', most intuitively, is the potential of a system to be transformed by political or governance interventions, which can include policy shifts, regulatory changes or changes in institutional structures that influence system behaviour (Voulvoulis et al., 2022). If a system has low transformative potential, it is caught in a lock-in state (see e.g. Folke et al., 2004). If it has high transformative potential (i.e. transformability), there are plenty of options for how to change this system towards something fundamentally new (Tuckey et al., 2023). Many systems, and arguably the Earth system itself (Steffen et al., 2018), are currently locked in unsustainable and unjust states; and we have yet to find ways to 'unlock' undesirable feedbacks and unleash the transformative potential of many interconnected systems to shift onto pathways for sustainability (Westley et al., 2011). Here, we think of the enabling actions to facilitate such a shift as leverage points for sustainability transformation, drawing on the work of Meadows (1999, 2008).

Leverage points are places to intervene in a system (Meadows, 1999). They occur within complex social-ecological systems and can be acted on in order to induce change. Leverage points can be classified into fundamental (deep) and superficial (shallow) ones (Figure 1). Interventions at deep leverage points have greater potential to change a system fundamentally, while interventions targeting shallow leverage points generally have less influence on the system as a whole. Therefore, the distinction between shallow and deep leverage points describes the extent to which interventions at these points can alter the trajectory of a system and transform it. Following Abson et al.'s classification (Abson et al., 2017), shallow places to intervene in a system include parameters and feedbacks. Deep places to intervene include the designs and intents of a system, not least because changing system design and intent automatically has repercussions for feedbacks and parameters (Abson et al., 2017; Meadows, 1999). Taken up

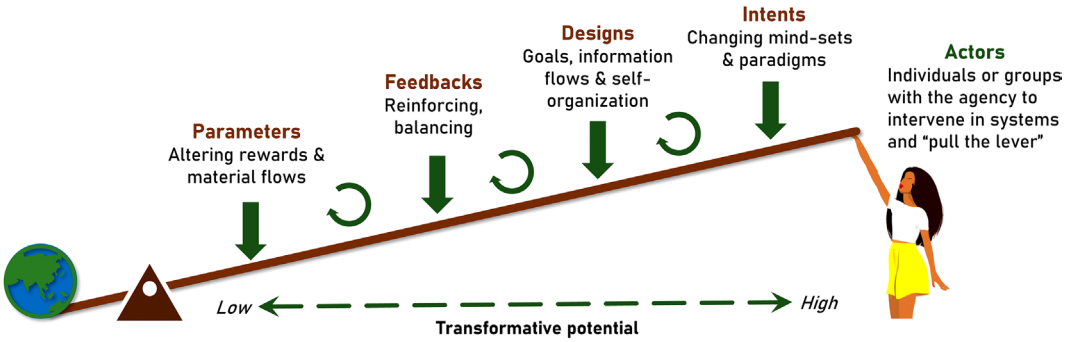

FIGURE 1 The four system characteristics (parameters, feedbacks, designs and intents) in which interventions can lead to transformation, based on their likely transformative potentials and the actors that have to intervene in the system for it to transform towards sustainability. Based on Meadows (1999), Abson et al. (2017), O'Brien (2018), Fischer and Riechers (2019). Female generated by DALL.E (Open Ai, https://openai.com/dall-e-2).

by the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES) (Chan et al., 2020; IPBES, 2022), the leverage points perspective has rapidly gained momentum in sustainability science (Folke, 2020; Leventon et al., 2021; Riechers et al., 2021). Yet, concrete approaches on how to identify leverage points and how to operationalise them through targeted interventions are still widely lacking.

To address this gap, we propose a concrete, step-by-step approach through the framework of 'chains of leverage' (Riechers et al., 2022). We define a 'chain of leverage' as a situation within a system in which multiple system elements across system depths (i.e. across parameter, feedback, design and intent) and governance levels (local to global) have synergistic impact on one another (Riechers et al., 2022; Rosengren et al., 2020). Considering the governance structures, processes and institutions through which policies are enforced is crucial for understanding the rules, guidelines, and strategies that shape decision-making (Patterson et al., 2017). For a given system, we want to understand how transformation can be achieved. Transformation may be achieved through strengthening elements within a system or by destabilising them (Newig et al., 2019)—this may mean, for example, destabilising the feedbacks that keep a system locked in and then activating the drivers that push it elsewhere (Olsson et al., 2014). The framing of chains of leverage is aligned to the concept of resilience, but adds the focus on different levels of system depth. In this article, we aim to explain and exemplify one way to identify transformative potential through a leverage points perspective. For this, we will (a) identify transformative potential through chains of leverage, and (b) explain the concept of chains of leverage through the example of efforts to improve agriculture in southwestern Ethiopia.

2 | IDENTIFYING TRANSFORMATIVE POTENTIAL THROUGH 'CHAINS OF LEVERAGE'

Because social-ecological systems are complex and adaptive (Berkes & Folke, 1998), interventions can have unintended consequences (Meadows, 1999, 2008)—making it crucial to anticipate and understand interventions and their interactions across different levels of system depth (see Figure 1). These interactions describe how one type of change in a system might precipitate further changes across different system depths (i.e. at the levels of parameters, feedbacks, design and intent) (Fischer & Riechers, 2019; Riechers et al., 2022). A chain of leverage hence describes a situation within a system in which elements at parameter, feedback, design and intent level and across governance level (local to global) re-enforce one another (see Rosengren et al., 2020). For example, a paradigmatic change of a system's purpose (or intent)—that is, a dialectical change of worldviews, mindsets and beliefs—might precede changes in system feedbacks and parameters, which would amount to 'deep to shallow change'. Alternatively, changes in parameters could also pave the way for a questioning of system goals and paradigms (shallow to deep change), or might help to establish emerging new goals or paradigms (Manlosa et al., 2018). In social-ecological systems, we can find sequences of how shallow, mid-level and deep systemic changes flow on from and reinforce one another, creating coherent chains of leverage (Riechers et al., 2022) (see Figure 2). Moreover, some paradigms or design structures might be more sustainable and equitable than existing ones—indicating a normative dimension as to what kind of transformation the system should undergo to become more sustainable. We included the governance level to account for teleconnections and telecoupling (Hull & Liu, 2018) as well as to capture possible power imbalances regarding multiple actors' capacity to transform elements (Avelino & Wittmeyer, 2017).

We assume that social-ecological systems typically do not have single, but diverse intents, designs, feedbacks and parameters. On all of these, several governance actions are being carried out by various actors simultaneously, thereby causing interactions between leverage points. These interactions can form chains of leverage that may be in conflict with each other. The 'chains of leverage' framework assists in identifying leverage points (i.e. places to intervene in a system) as well as prioritising interventions (i.e. concrete action) with the highest impact rather than relying on incremental changes. Such knowledge allows identifying drivers and agents of power in the transformation process as well as helping to phase out unsustainable elements of the system, and instead empowering a sustainable chain of leverage to foster transformation. Moreover, the 'chains of leverage' framework can help to highlight mismatching elements (such as conflicting paradigms, rules or institutions) and highlight possibly more effective alternatives (i.e. coherent chains of leverage). This could reduce inefficiencies and help to avoid unintended consequences, such as policy resistance or rebound effects. The 'chains of leverage' framework also enables cross-sectoral thinking, enhancing resilience by strengthening adaptive capacities across multiple governance levels and power regimes rather than creating dependencies. Thereby, stakeholder engagement both at central governance institutions as well as across actors with less formal power can be enhanced by illustrating how different actors influence one another, fostering collaboration and social learning.

3 | UNDERSTANDING CHAINS OF LEVERAGE

In Figure 2, we describe an exemplary and simplified system in which the unsustainable (blue) elements form a coherent chain of leverage. The sustainable (yellow) elements have less influence in the system (they are depicted as smaller), and do not form a coherent chain of leverage, as we see a missing element (a system design), and a missing interaction between a sub-national intent, and a local intent (spotted arrow). This depiction of a system helps to identity leverage points, by, for example, (i) increasing the influence of the sustainable (yellow) system intent; (ii) decreasing or dismantling the strength of the very influential but unsustainable, national system intent; or (iii)

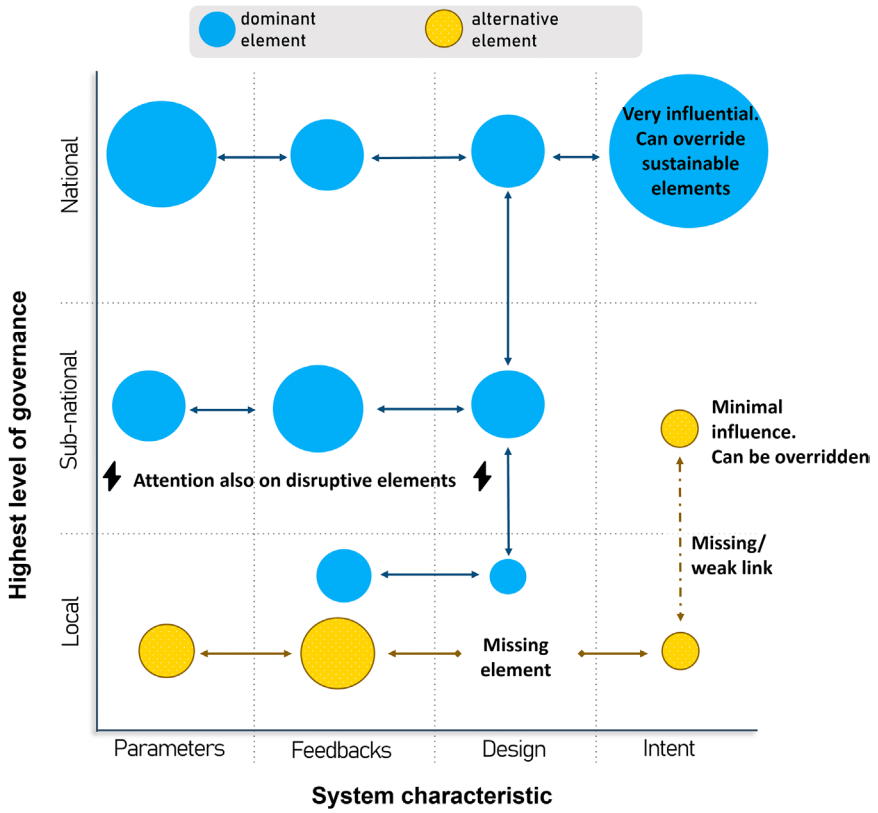

FIGURE 2 Graphical simplification of a generic system. Elements within the system can be categorised based on their main system characteristic (system parameters, feedbacks, designs or intents) and by their highest level of governance (here exemplary from local to national). The size of the circles indicates the strength of the influence an element has on the system, that is, the bigger the circle, the stronger the influence. Blue: dominant elements; yellow: alternative elements. The lightning bold ⚡ indicates disruptive elements (see Figure 3) that can occur across all system characteristics and levels of governance.

starting an initiative that creates a sustainable (yellow) system design element, thereby creating a coherent chain of leverage. As we show via a concrete example below, to understand the transformative potential of a system via 'chains of leverage', we suggest four steps of analysis.

Step 1: Assess important elements of parameters, feedbacks, designs and intents of the system (i.e. the transformative potential of system elements);

Step 2: Analyse if these elements are currently dominant, suppressed, and/or destructive/conflicting;

Step 3: Examine if elements are linked, to ascertain if there are (coherent) chains of leverage;

Step 4: Identify leverage points to intervene in the system to create one or more coherent, sustainable chains of leverage and thereby foster sustainability transformation.

The four steps to identify transformative potential should be based on data. How such data are collected or synthesised depends on the social-ecological system and general research contexts. Analysing existing literature or qualitative (e.g. using Q-methodology in interviews, participatory workshops, expert assessments), quantitative (e.g. participatory modelling) approaches of data collection or a combination of these, may be some ways to highlight key elements, their strength of influence and how they are interrelated in a given system (e.g. Korhonen-Kurki et al., 2024; Riechers et al., 2022; Rosengren et al., 2020). We examine these steps via one example, namely the drive for agricultural gains in Ethiopia. More information on this example, and a second one related to the energy transition in the EU is found in the Supporting Information S1 (Part 2) online.

4 | EXPLAINING CHAINS OF LEVERAGE THROUGH THE DRIVE FOR AGRICULTURAL GAINS IN ETHIOPIA

Because much social-ecological systems research is place-based (Norström et al., 2022), we present an example from an inter- and transdisciplinary study that investigated food systems over the course of 6 years in southwestern Ethiopia. Both the national government and local communities aimed to improve food security, yet their approaches revealed possibly conflicting intents and mismatches (Jiren et al., 2021). The Jimma zone—an administrative area—has ~3 million inhabitants, of which nearly 90% live in rural areas and depend on subsistence farming as their main livelihood (Oromiya Bureau of Finance and Economic Development (OBFED), 2012). Traditionally, subsistence farming is focused on maize, teff, wheat, barley and sorghum, while coffee and khat are cultivated as cash crops. In addition, most households keep small numbers of livestock (cattle, sheep and poultry) and many draw on forest ecosystem services for their livelihoods (Ango et al., 2014). In terms of food security, although food insecure by international standards, people in Jimma zone are relatively better off than people in many other parts of Ethiopia, for example in terms of agricultural production, dietary intakes and levels of poverty (Ethiopian Central Statistical Agency/World Food Programme (CSA/WFP), 2014).

The Ethiopian government established formal institutions to strengthen agricultural production and efficiency stipulated through the Growth and Transformation Plan (GTP), the Rural Development Policy and Strategies (RDPS) and plans for

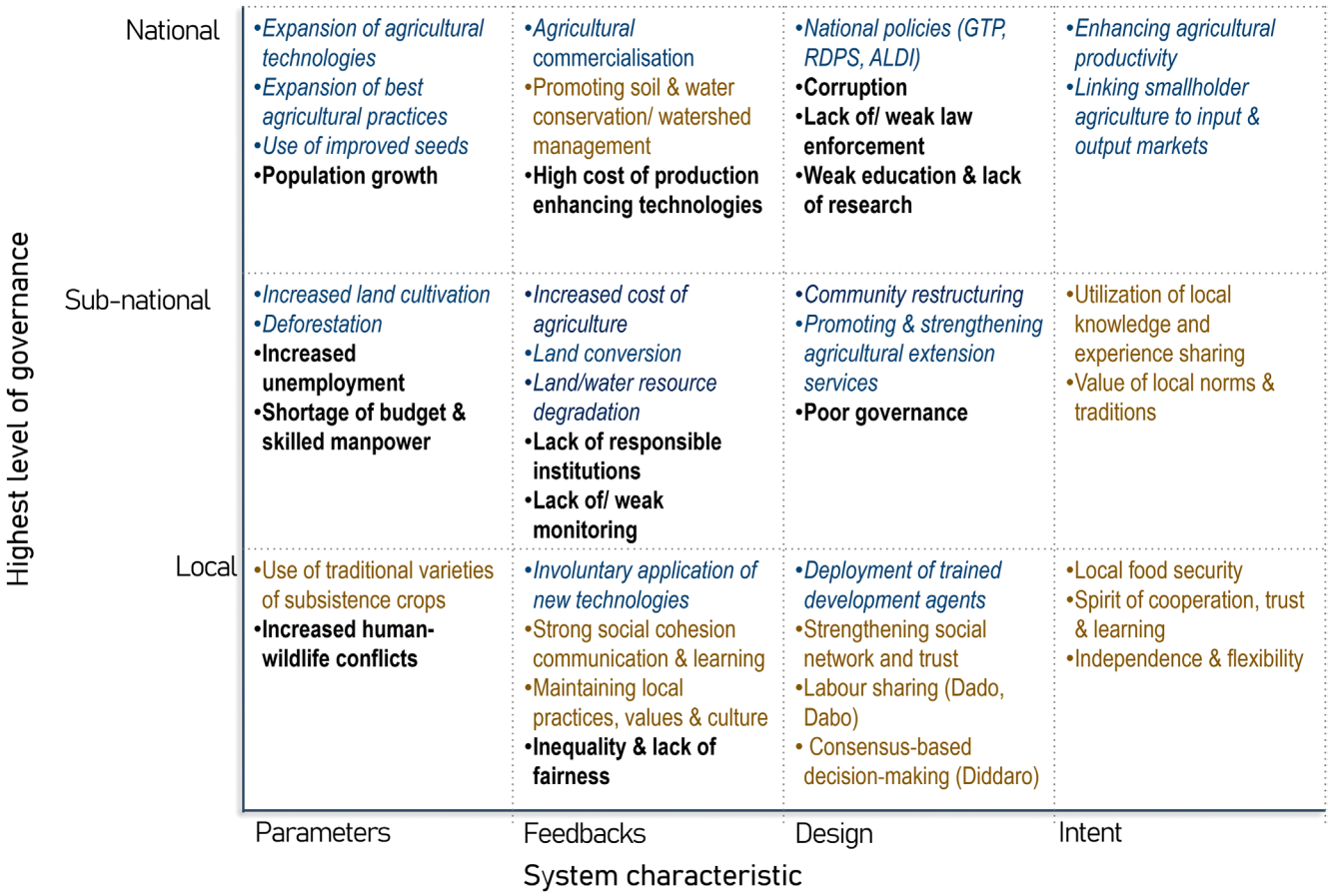

FIGURE 3 Graphical depiction of a situation in the Ethiopian food system. Exemplary elements by system characteristic and highest level of governance as identified by Jiren et al. (2021) and Shumi et al. (2023); blue and cursive: dominant elements; yellow: alternative elements; black and bold: disruptive elements. For more specific information see Tables S1–S4.

Agricultural Development Led Industrialisation (ALDI) (Ministry of Finance and Economic Development (MOFED), 2003; Ministry of Finance and Economic Development (MOFED), 2010; Federal Democratic Republic of Ethiopia (FDRE), 1995). However, long-standing local informal institutions around sharing labour and knowledge (called Dado, Dabo and Diddaro) continued strengthening trust, collaboration and shared labour at the local level (Negera et al., 2019). This, in turn, created a mismatch between the national priority of cash flow and economic productivity versus the local focus on shared and secure local livelihoods (Jiren et al., 2021). We now use our suggested four steps to analyse the case study.

4.1 | Step 1: Assess parameters, feedbacks, designs and intents of the system

First, we identify core system structures and elements and characterise those by their system depth of parameters, feedbacks, design and intent. The more specific such system elements are defined, the better the assessment, as very abstract ones might address multiple system characteristics. For the example of agricultural development in Jimma zone in Ethiopia, we identified a number of key elements based on Jiren et al. (2021) and Shumi et al. (2023) (see elements in Figure 3 and for a more complete list of the parameters, feedbacks, designs and intents, see Tables S1–S4).

4.2 | Step 2: Analyse if these elements are dominant, alternative and/or destructive/conflicting

In a second step, we plot the different elements of the system according to their level of governance (in this example local to national) and identify possible dominant, alternative and or destructive elements (Figure 3). We can analyse our system by asking, what are the predominate elements? Are (sustainable) elements 'overridden' or suppressed through predominant elements because they currently lack power to substantially shape system dynamics? Who are the actors involved?

4.3 | Step 3: Identifying chains of leverage

Based on the identified elements in Step 2, we focused on similarities or synergistic effects between the elements. By bundling elements that have great similarities and synergistic effects, we boiled down the list of elements in Figure 4 for simplicity. We asked ourselves

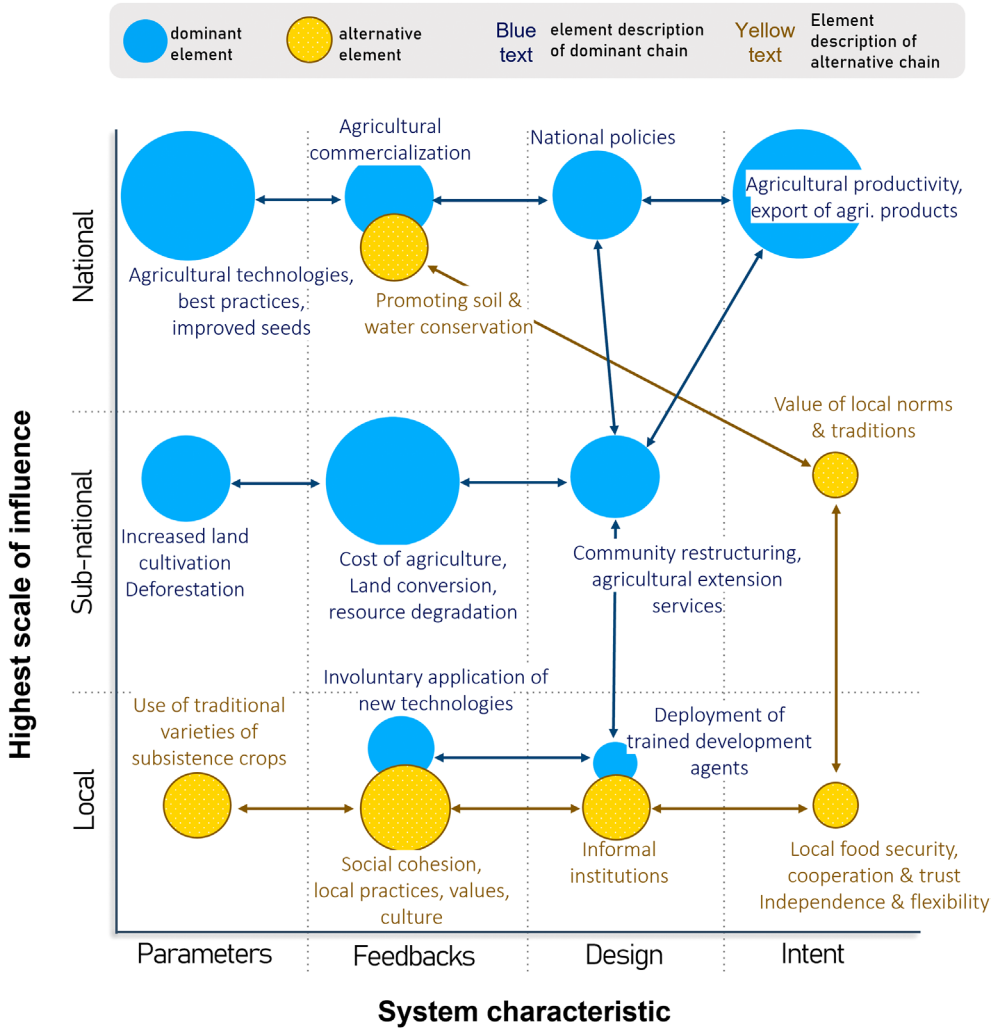

FIGURE 4 Graphical depiction of a situation in the Ethiopian food system. Chains of leverage: dominant (blue) and alternative (yellow, spotted) elements (circles) and interactions of elements (arrows). The size of the circles represents the strength of elements' influence on the system. The figure shows how national and subnational elements with strong influence currently override the alternative (yellow, spotted) intents of the system. Yet, on local level, the alternative elements (informal institutions in this case) have a stronger influence, meaning that the dominant chain is inefficient on local level as their designs and feedbacks are mostly countered by local, alternative ones. Disruptive elements are omitted in the graphic for simpler visual representation.

the following: Do the elements form coherent chains of leverage? Can we identify more than one chain? Can we identify an alternative chain that does not seem to have the power to transform the system? This exercise can be as comprehensive and detailed as necessary. In this example, we based the assessment on our long-term knowledge within the region. Based on the previous exercise that helped identify dominating and alternative elements, we expressed the influence of each element by the size of the circles in Figure 4.

We deduce two core findings: (1) we were able to identify two coherent chains of leverage—a currently dominant one and an alternative one. The national priority of cash flow and economic productivity for Ethiopia and the local focus on shared and secure local livelihoods created two separate chains of leverage, with a more national chain prioritising cash flow and economic productivity and another, alternative and more local one focussing on shared and secure local livelihoods. Due to the inherent power imbalances between the national and local governance levels, the formal institutions established by the Ethiopian government (different circle sizes in Figure 4) are now eroding long established informal ones (Jiren et al., 2021). (2) In this example, dominant national and subnational elements have a strong influence on the social-ecological system and therefore override the alternative intents of the system. Yet, at the local level, the alternative elements (informal institutions in this case) have historically had a strong influence, but the dominant chain driven by the national level is now eroding the designs and feedbacks of traditional practices at the local level.

4.4 | Step 4: Identify leverage points to foster sustainability transformations

The slowly eroding locally grounded chain of leverage that links the system intent of food security with informal institutions and

coherent system feedbacks and parameters presents an alternative chain of leverage that may be more sustainable and equitable in the long run than the dominant, national one, focusing on agricultural efficiency. The existence of this alternative chain indicates the transformative potential of the given system. System transformation may be 'unleashed' through leverage points that generally (i) strengthen the alternative chain, (ii) deconstruct or disempower the existing, unsustainable chain and (iii) eliminate or weaken disruptive elements (Figure 5). In southwestern Ethiopia, leverage points (i) could strengthen local knowledge, values, norms and traditions (i.e. the informal institutions such as Dado, Dabo and Diddaro) that constitute the local and sub-national system intent by for example, scaling them up to the national level (Lam et al., 2020), and strengthening existing links to national feedbacks. (ii) By deconstructing/re-constructing the formal institutions set in place by the national government (e.g. GTP, RDPS and ALDI) and their system intent that is focused around enhancing agricultural productivity and economic gain, a window of opportunity may be open for alternative elements to take their place (Jiren et al., 2020; see also Lübker et al., 2021). (iii) Within the system, chains of leverage are likely not only competing among each other but also have destructive or conflicting elements that hinder the effectiveness of chains of leverage. In some cases, disruptive elements have an overall negative outcome for sustainability and should be reduced; in other cases, one could help unleash transformative potential by harnessing disruptive elements to weaken the dominant, unsustainable chain of leverage (Figure 5).

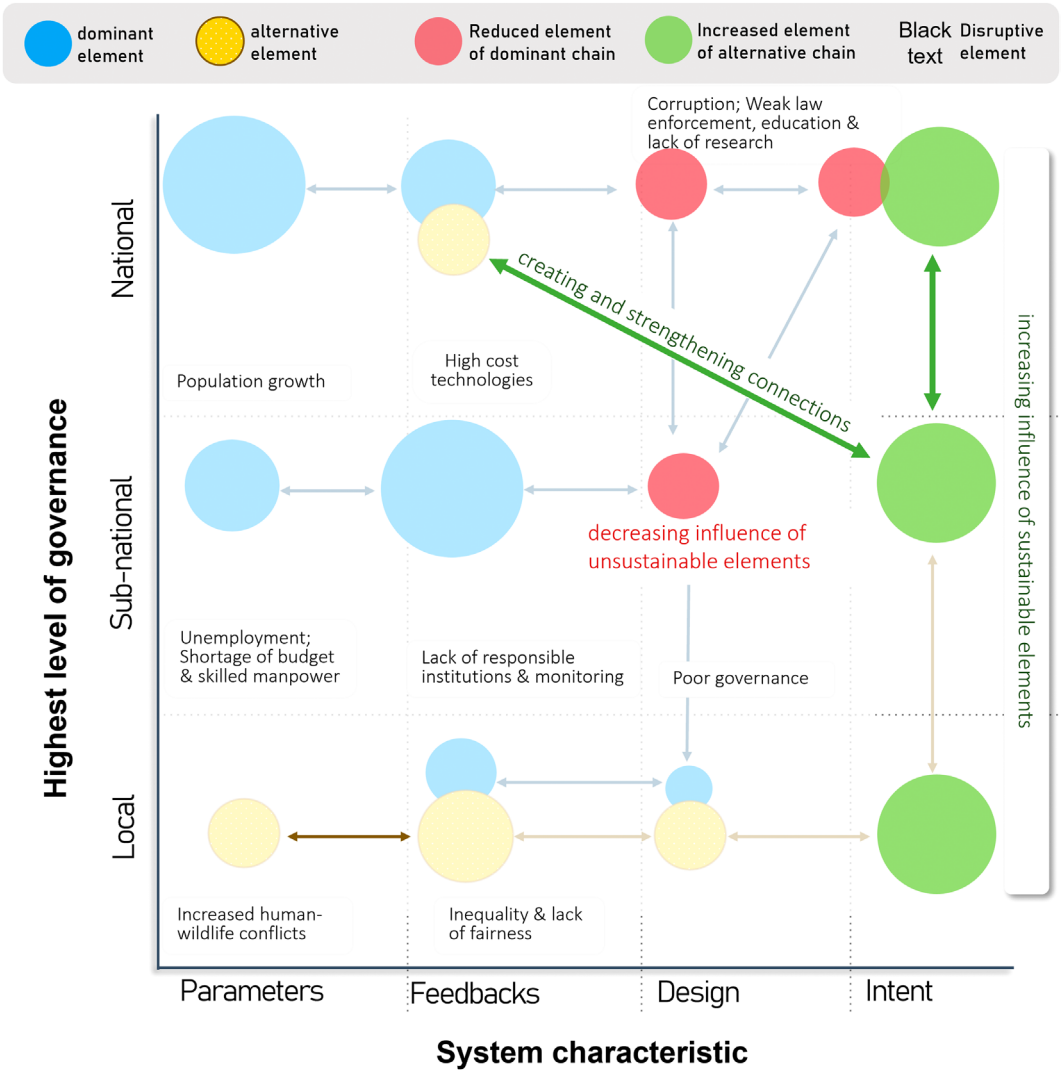

FIGURE 5 Graphical depiction of potential leverage points in the chains of leverage in an Ethiopian food system. This figure builds on Figure 4. Chains of leverage: dominant (blue) and alternative (yellow, spotted) elements (circles) and interactions of elements (arrows). The size of the circles indicates strength of influence on the system (larger = stronger). Potential leverage points in the Ethiopian food system: bolstering the alternative chain by strengthening local and subnational system intents, upscaling the local and sub-national intent into the national sphere (green circles represent the increase of influence); strengthening the coherence/connection to existing sustainable national elements within this alternative chain (green, bold arrows represent a strengthening or a creation of links between sustainable elements); decrease of the influence of unsustainable elements to deconstructing or disempowering the dominant, unsustainable chain (red circles represent the decrease of influence). Disruptive elements: black text in boxes.

5 | A NEW WAY OF UNDERSTANDING TRANSFORMATIVE POTENTIAL AND IDENTIFYING LEVERAGE POINTS

Our analysis showed that leverage points can take several forms, including (i) creating new coherent chains (e.g. by creating missing elements or missing links between elements), (ii) empowering existing ones (e.g. by scaling up elements or increasing their influence), (iii) deconstructing unsustainable dominant chains (through decreasing influence of elements) or (iv) mitigating disruptive elements.

We purposefully chose an example with coherent chains of leverage to explain our concept. In other examples, we may not find a fully coherent alternative chain of leverage. In case sustainable elements within a system do not form a coherent chain, missing elements (be it within parameters, feedbacks, designs and intents) should be created. For some elements, this is easier than for others, as especially new or alternative goals and structures require 'out-of-the-box thinking'. The system intent often mirrors prevalent mental representations of imagined futures (e.g. Beckert, 2013), and the societal/national goal can be mismatched with individuals' goals on the local level, as visible in our example (Figure 5). Thus, social and political macrostructures within a system may limit the agency of individual actors and their participation (Avelino et al., 2016) as well as their imagination of alternative system goals or designs (Beckert, 2013). Such partly mental lock-ins (Lübker et al., 2021; Westley et al., 2011) are exemplified by the economic growth paradigm being nearly unanimously agreed upon while alternative concepts are perceived as illegitimate (Asara et al., 2015). Influential system intents, hence, can be perceived as self-evident, limiting overall capacity to think outside the box (Pesch, 2018). Yet, the availability of diverse alternatives can enhance the resilience of social-ecological systems when a large powerful system element is removed or its influence diminishes, or when that system element is transformed and can then leverage back down to other system nodes in different parts of the system. Hence, strengthening alternative visions or communities of practices or knowledges can be helpful (Bennett et al., 2016). In other cases, elements that hold transformative potential to shape the future may already exist in 'niches' of the studied systems (Avelino et al., 2016), but may neither be widespread nor well-known (Figure 4). Hence, the elements have not yet had enough influence to transform the broader system in which they operate (Lam et al., 2020) or are being overruled by the dominant system (as described above). To increase the influence of desirable elements, individuals or groups need sufficient agency to intervene in the system (McLaughlin & Dietz, 2008; Narayan & Petesch, 2007). Enhancing agency could be achieved through social innovations, new technologies, economic tools, organisations, movements or new ways of acting that contribute to the creation of a future that is just, prosperous and sustainable (Bennett et al., 2016).

Agency is inherently political, making it crucial to carefully examine the political context when analysing potential chains of leverage in transformation processes. While many political systems around the world are characterised by centralised institutional power, transformation can also be driven by agents who hold diverse forms of power and agency across different governance levels (Morrison et al., 2019). In fact, power for transformation is often distributed across actors and their social relationships rather than concentrated solely in centralized actors, and can span across multiple governance levels, actors and sectors. This dispersion of power complicates the understanding of transformative processes, but also presents valuable opportunities to address equity issues and reshape the uneven capacity of different actors to influence the goals, processes, and outcomes of transformation (Linnér & Wibeck, 2021; Loos et al., 2024). While power imbalances are a component of any governance system and cannot be entirely eliminated (Turnhout et al., 2020), societal transformation, at its core, entails a dimension of empowering further actors to influence the system. This in turn, may involve plural perspectives on desirable futures as well as the process on how to get there, while acknowledging different needs and capabilities of those who are involved in the multi-level governance of the respective social-ecological system. The addition of the 'chains of leverage' approach starts to address the gap identified in the IPBES Transformative change assessment (IPBES, 2024a) that while there are a growing number of visions of desirable futures, the pathways of how to achieve these, especially at the planetary level, are not as well developed and certainly not as transformative. Chains of leverage allow for coherent pathways of actions and interventions, taking into account their potential for non-linear change, that could lead to more transformative futures.

Regarding southwestern Ethiopia, Shumi et al. (2023) found that potential leverage points, among others, could be found in the area of recognizing and aligning with Indigenous peoples and local communities, and their multiple worldviews (Fernández-Llamazares et al., 2021; Tynan, 2021). Most local stakeholders interviewed by Shumi et al. (2023) identified leverage points to weaken the dominant designs and intents. However, the dominant chain of leverage was upheld by the paradigms of a green revolution or growth-based development, with no intent to loosen top-down control (of other humans, political structures or over nature in general). This, in turn, created the feeling among many stakeholders of a lack of agency to act upon identified deep leverage points, despite local people perceiving and being affected by the current trajectory of the system (see also e.g. Hartel et al., 2023; Riechers et al., 2019). Further, in our example, disruptive elements such as political turmoil hinder the creation of coherent chains of leverage through, for example, unclear or interrupted power relations. While disruptive elements can create opportunities for alternative designs and intents to co-exist, they can also hamper any implementation of rules and laws.

By providing concrete steps to identify leverage points and therefore the transformative potential of their associated interventions, we aim to contribute to the vital endeavour of transforming towards more resilient and sustainable social-ecological systems. Our approach can be linked to 'nexus approaches' as presented by IPBES (2024b) as we also aim to understand interlinkages and interdependencies in a holistic manner 'to develop integrated and adaptive decisions that aim to maximize synergies and minimize trade-offs' (p. 9). We believe that our chains of leverage framework could help

to amplify and operationalise the findings of the nexus assessment by (i) considering/ascertaining nexus element interlinkages when focusing on places to intervene in a system with high transformative potential (i.e. leverage points, see also IPBES, 2022), (ii) providing a step-by-step guide to understanding cascading and compounding impacts and synergies between elements of a system and (iii) guiding decision-makers towards concrete interventions in leverage points while acknowledging that the intervention may lead to a deterioration of other elements (e.g. trade-offs). Future research could focus on adding a stronger power/justice lens to the dynamic of chains of leverage, and/or analyse and compare dominant chains, as dominant chains may be 'archetypical', that is, multiple systems may have archetypical chains of leverage that could provide a blueprint for enabling pathways towards transformative change. Moreover, there may be instances where multiple chains of leverage can co-exist rather than strictly compete with one another—possible interactions among multiple co-existing chains thus also should be examined more carefully in future work. For another example of a chains of leverage analysis of the EU energy system, see the Supporting Information S1 online.

6 | CONCLUSION

This article introduced a novel operationalisation for assessing the transformative potential of social-ecological systems through a leverage points perspective. With the framework of 'chains of leverage', we provide a concrete step-by-step approach to disentangle the complex dynamics within systems. By unveiling how to assess chains of leverage, our framework helps in identifying the right places to intervene in systems, where small shifts or interventions can have significant and transformative impacts. The 'chains of leverage' framework illustrates how changes at different system depths can cascade and reinforce one another, thereby offering a roadmap for intervention towards transformative change by either creating new coherent chains, empowering existing ones, deconstructing unsustainable dominant ones or mitigating disruptive elements. By providing a systematic means to identify leverage points and assess the transformative potential of associated interventions, our framework contributes to the essential effort of transitioning towards more resilient and sustainable social-ecological systems.

AUTHOR CONTRIBUTIONS

Maraja Riechers and Joern Fischer conceived the ideas and designed the concept; Maraja Riechers, Tamara Schaal-Lagodzinski and Joern Fischer synthesised the data for the examples; Maraja Riechers led the writing of the manuscript, Tamara Schaal-Lagodzinski, Joern Fischer, Jacqueline Loos and Laura Pereira contributed to the writing of the article. All authors contributed critically to the drafts and gave final approval for publication.

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CONFLICT OF INTEREST STATEMENT

The authors state no conflict of interest.

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No new data were generated or analysed in support of this research.

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SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

Tables S1–S4. Exemplary leverage points by system characteristic as identified by Jiren et al. (2021) and Shumi et al. (2023).

Table S5. Exemplary leverage points by system characteristic.

Figure S1. Chains of leverage: Dominant 1 (yellow) and alternative (purple) chains of leverage and interactions of elements. Dominant chain 1 represents the focus on energy security tied to maintaining the status quo of fossil fuel and nuclear energy production. The purple chain presents a second chain of leverage in this complex system through changed energy consumption and decentralised energy production. The size of the circles represents the strength of elements' influence on the system.

Figure S2. Chains of leverage: Dominant 1 (blue) depicts the transition towards RE and the fossil fuel phase-out initiated by the European Green Deal. Grey elements depict system parameters and feedbacks that are not inherently linked to a particular chain but can be influenced by them (level of social acceptance can be high, strengthening the alternative chain or low, strengthening the dominant one). The size of the circles represents the strength of elements' influence on the system.

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