Entry points for accelerating transitions towards a more sustainable future

Enayat A. Moallemi[1,*], Michelle Miller[1], Katrina Szetey[1], Sabrina Chakori[1], Jeda Palmer[1], Michael Battaglia[1,5], Brett A. Bryan[2,5], Lei Gao[1,5], Andy Hall[1,5], Peat Leith[1,5], Rob Raven[3,5], Patrick M. Reed[4,5]

[1] The Commonwealth Scientific and Industrial Research Organisation (CSIRO), Australia
[2] Deakin University, Melbourne, Australia
[3] Monash University, Melbourne, Australia
[4] Cornell University, Ithaca, The United States
[5] These authors contributed equally and are ordered alphabetically.

* Corresponding author, email: enayat.moallemi@csiro.au

SUMMARY. Accelerated transitions that enable far-reaching and systemic changes to a more sustainable future are urgently needed to ensure inclusive human development and Earth system stability[1]. Different processes for accelerating transitions have been proposed over the past decade[2,3]. However, evidence-based guidance on of what these processes are across scientific and policy spheres and their specification in different contexts remain fragmented and ambiguous. Here, we identify nine recurring processes for accelerating change based on an analysis of 60 cases across four transition domains, three geographical scales, and seven continents. We call them *entry points* as they are areas to initiate research and practical interventions aimed at facilitating transitions. Our results show that the prevalence of different entry points varies significantly across domains and scales, indicating there is scope to further improve our understanding of what works, where, and why, to facilitate transitions. The results also highlight three ways that research and policy can take diverse knowledges seriously by integrating multiple complementary entry points in informing far-reaching change. These results can offer guidance for establishing accelerated transition agendas based on deliberative dialogue that draws on diverse perspectives[4].
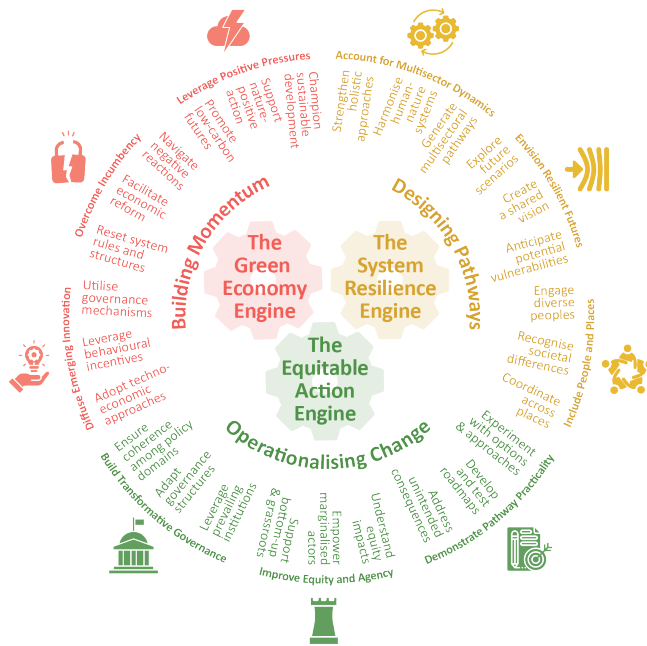
Main

Fossil fuel energy, intensive industrial agriculture, and global commons overextraction (i.e., linear patterns of taking, making, and disposing) dominate how society attains and consumes energy, food, and materials. These systems have contested sustainability outcomes and can contribute to persistent global challenges such as climate change, acute socio-economic inequalities, and destruction of natural habitats[5]. Around the world, governments, industries, and communities are seeking widespread change within unsustainable systems in a just and orderly manner to reconfigure or eventually replace them[6-8]. This collective effort is calling for *transitions* (i.e., far-reaching and systemic change across multiple dimensions from an existing system to a more sustainable one[9]) and *transformations* (i.e., shifting human and environmental interactions and feedbacks for creating safe and just operating spaces[10]). While the two terms may stem from different areas of research[11], they both emphasise and enrich each other's perspective on achieving inclusive human development and Earth system stability (hereafter, in short, we use *transition* to cover both terms).

Independently, the means of accelerating transitions have been conceptualised differently across different scientific fields[12]. It has been examined in sustainability science and socio-ecological studies, for example, through leveraging interconnections and complementarities between various aspects of sustainable development[6] and triggering key system leverage points that create positive human-natural feedback interactions[13]. Acceleration of change has been researched extensively in socio-technical system studies, for example, as concerted effort for diffusing radical innovation[2] and overcoming the inertia and incumbency of an existing system that resists change[7]. It has been approached in the governance literature in relation to the role of agency, institution, power, and politics in impeding or expediting change[14,15]. Beyond science, acceleration has also been subject of policy and practice linked to different areas. For example, the Sixth Assessment Report of the Intergovernmental Panel on Climate Change dedicated a chapter to accelerating transitions[3], science and innovation for accelerating change was a central focus at the United Nations (UN) Food Systems Summit[16], and the UN Global Sustainable Development Report 2023 have called for an acceleration of progress towards sustainability[17].

Despite the richness and diversity of previous works on transition, empirical guidance on the processes through which they can be accelerated across diverse domains and scales remains fragmented and has not

been synthesised. As a result, this fragmentation has limited the identification of transferable lessons across systems, disciplinary boundaries, and places that can enrich complementary perspectives. While acknowledging that transitions are spatially diverse phenomena[18], such empirical insights and transferable lessons are critical if we are to scale up and accelerate change within the rapidly closing time window for action to tackle climate change[19] and realise the Sustainable Development Goals (SDGs)[20].

Here, we synthesise key recurring processes that can facilitate the acceleration of transition to a more sustainable future through an in-depth analysis of 60 empirical cases of attempts to understand, design, and implement change. We call these recurring processes *entry points* as they represent various ways through which transdisciplinary thinking, research, and action about transition can begin and progress (Methods, Figure 1). We elaborate each entry point by specifying their different means of implementation in various contexts. We also identify patterns of interaction across entry points that bring together perspectives with complementary insights that support desired change at the requisite speed.

The cases, selected to synthesise entry points, provide a representation of three scales (i.e., global scientific assessments, international and national strategies, subnational and local plans) across seven continents and led by different actor groups (Methods, Figure 2). They also originate from different transition domains with four foci on outcome, either sectoral (i.e., agriculture and food, energy and climate) or societal (justice and equity, sustainable development) (Methods). Together, they offer a significant body of knowledge and practice, important for identifying directions and empirical guidance for transitions in different contexts.
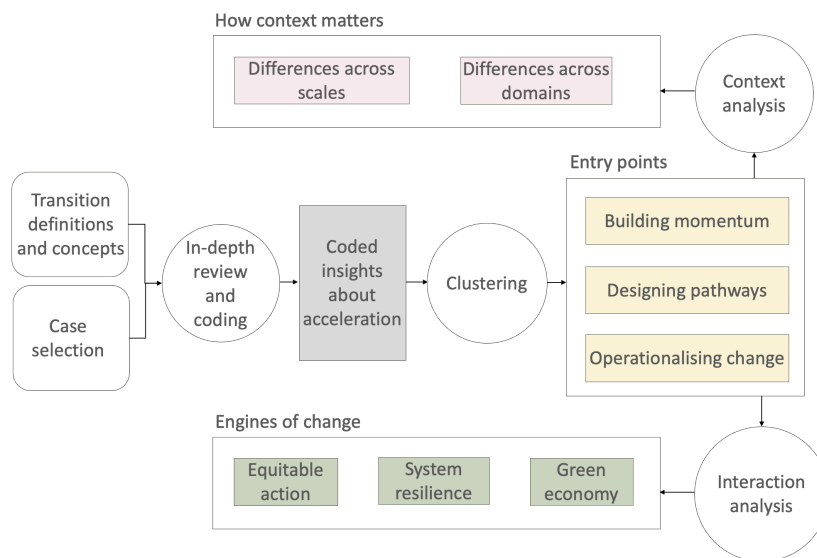
Figure 1. An overview of the methods used for analysing cases and synthesising entry points. See Methods for details and description of each step.
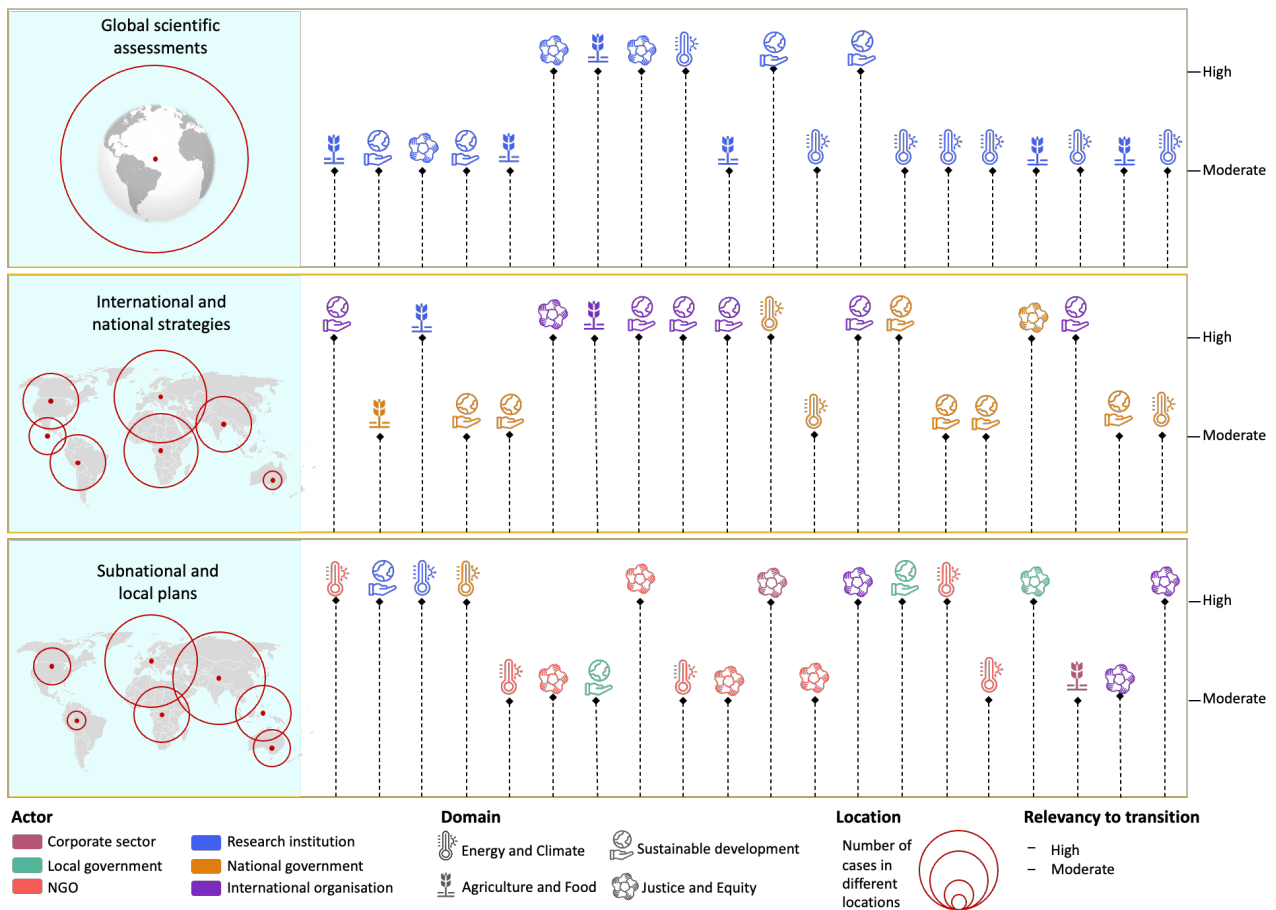
Figure 2. An overview of the 60 cases analysed related to sustainability transitions. Cases were categorised in three boxes from top to bottom representing three scales of global scientific assessments, international and national strategies, and subnational and local plans (each with 20 cases). Cases were also categroised into four transition domains based on their focus on outcome: agriculture and food (10 cases), energy and climate (17 cases), justice and equity (14 cases), and sustainable development (19 cases). While we acknowledged multiple aspects that each case has with regard to differnet domains, we decided to assign the case to only one domain that was central to the case to improve the clarity of analytical process (see Methods for details). Each dashed line represents one case. Cases are arranged in reverse chronological order (most recent on the left). Icons at each dashed line indicate domain focus, and icon colour identifies the leading transition actor. Cases were selected through a hybrid method of systematic and integrative search for scientific and grey literature respectively (Methods). Selected cases were related to transition to different extents, which we subjectively rated with moderate and high (Methods). The name and online access to all cases are available in Supplementary Data 1.

Results

Defining entry points

Through an in-depth analysis of empirical cases based on a coding and clustering of their insights (Methods), we synthesised nine entry points (and their specifics), as processes to initiate research and practical interventions aimed at facilitating transition processes. Whilst we acknowledge significant differences between contexts, place-based recommendations, and scholarly origins, entry points were identified based on analogous and transferable lessons that can be drawn meaningfully across cases. We presented the entry points in three general themes[21]: building momentum, designing pathways, and operationalising change (Table 1; Figure 3). We chose these three themes as they also echo different approaches for transition to sustainability in the literature[22], ranging from structural (i.e., shifts in underlying foundations), to systemic (i.e., management of deep uncertainty and complexity of system interactions), to enabling (i.e., social capacity and individual empowerment for action), respectively.

Table 1. Entry points for accelerating sustainability transitions, identified across the 60 cases. The entry points (and their specifics) emerged from 60 cases through content coding and clustering (Methods). Entry points can be interconnected. Thus, the distinction between them is not always clearly defined, and this is an inherent outcome of the clustering approach (Methods). For instance, multiple entry points talk about policy and governance, but each for a unique purpose.

Theme	Entry point	Specifics	Description and example
Building momentum	Diffuse Emerging Innovation	Adopt techno-economic approaches	• Use technological and market-based approaches, such as green fiscal reforms and technology efficiency improvements, to drive change[5]
		Leverage behavioural incentives	• Enable behavioural change via demand-side interventions or utilisation of external shocks like drought to encourage more sustainable practices[6]
		Utilise governance mechanisms	• Build coalitions for action via participatory frameworks and integrated approaches to policy, governance, and partnerships[23]
	Overcome Incumbency	Reset system rules and structures	• Overcome structural and institutional forces that constrain change and are amplified by powerful vested interests[24]
		Facilitate economic reform	• Prepare the infrastructure and financial systems that underpin the whole economy for a shift towards increasing sustainability and equity[25]
		Navigate negative reactions	• Address fears of negative unintended consequences for society, importantly for vulnerable populations, that create public backlash[26]
	Leverage Positive Pressures	Promote low-carbon futures	• Leverage efforts to limit global warming (e.g., compliance with the Paris agreement)[27]
		Support nature-positive action	• Minimise environmental degradation and encouraging processes that leverage ecosystem resilience and functionality[28]
		Champion sustainable development	• Encourage the inclusion of development across social, economic, and environmental dimensions in sustainability transitions[29]
Designing pathways	Account for Multisector Dynamics	Strengthen holistic approaches	• Adopt a systems approach to understand and explain multidimensionality of transitions, systemic responses, and rebound effects[30]
		Harmonise human-nature systems	• Interpret interactions of technology, people, and environment and identify trade-offs and synergies via integrated assessments[31]
		Generate multisectoral pathways	• Develop pan-sectoral options that minimise negative trade-offs and maximise positive synergies[32]
	Envision Resilient Futures	Explore future scenarios	• Use what-if scenario analysis and sensitivity analysis to provide an understanding of different future trajectories[33]
		Create a shared vision	• Develop normative directions that stakeholders identify with and can contribute to through collective social learning[34]
		Anticipate potential vulnerabilities	• Anticipate and prepare for risks, vulnerabilities, or shocks that impact society, the economy, or the environment[35]
	Include Peoples and Places	Engage diverse peoples	• Ensure diverse actors are included in decision-making and/or planning of transitions to define and advance shared outcomes[36]
		Recognise societal differences	• Understand behavioural and cultural factors (e.g., expectations, lifestyle) as drivers of change that can enhance or impede transitions[37]
		Coordinate across places	• Coordinate pathways between places to improve connections across geographical scales, levels of government, and jurisdictions[38]
Operationalising change	Demonstrate Pathway Practicality	Experiment with options and approaches	• Test technological, social, institutional, and policy innovation and evaluating their feasibility[39]
		Develop and test roadmaps	• Develop plans to operationalise transitions via short- to long-term actions, investments, and fully costed business cases[26]
		Address unintended consequences	• Anticipate and managing negative unintended consequences, side effects, and challenges arising from transition implementation[40]
	Improve Equity and Agency	Address equity impacts	• Foreground equity as the central focus of transitions, with inclusive processes (e.g., for gender, ethnicity, disability) in implementation[41]
		Empower marginalised actors	• Use processes, e.g., redistribution of access to resources and community consultation, innovatively to ensure marginalised actors are included[42]
		Support bottom-up and grassroots	• Support and creating mechanisms for grassroots action and embedding bottom-up community stakeholder inputs in decision procedures[43]
	Build Transformative Governance	Leverage prevailing institutions	• Utilise existing institutional and political processes to leverage the governance and policy support required for effective transitions[44]
		Adapt governance structures	• Adapt governance structures to context, including transdisciplinary partnerships, centralised and decentralised governance[45]
		Ensure coherence among policy domains	• Coordinate implementation of policies across branches/levels of government, jurisdictions, decision-making processes, through time[6]

Building momentum

Socio-technical transitions literature emphasises that transitions, which are often facilitated by innovation, risk failure if deeper enabling conditions are not created and the policies and practices that 'lock in' old systems are not addressed (i.e., destabilised) in ways that make room for change[7]. The need to enable and unlock transition acceleration also emerged from analysis of our cases. We referred to it as building momentum and identified three related entry points so that innovation can be more widely adopted, and eventually existing unsustainable systems are reconfigured or replaced.

Diffuse Emerging Innovation. Accelerating transitions is often discussed in terms of how to diffuse emerging innovation. In fact, this is the most common entry point (39 cases) across the cases analysed. The cases document various ways by which innovation can be scaled up and spread across the system (Table 1; Figure 3). Among them are adopting techno-economic approaches to reduce costs and create new markets for innovation and leveraging behavioural incentives to stimulate demand for change and wider adoption of innovation. These two ways can be seen, respectively, in the examples of green fiscal reforms to promote clean energy investments in Kenya[35] and climate education and engagement in different countries to induce positive social dynamics for low-carbon societies[13]. Utilising governance mechanisms, as seen in an example of participatory governance with the local community for net-zero energy transitions in Slovakia's Upper Nitra Coal Region[23], is a third way that is observed less frequently in our cases but offers a critical mechanism to build agency for adopting and diffusing innovation.

Overcome Incumbency. Existing incumbent systems constrain transitions, which can generate inertia and resistance in various forms, yet only a small number of cases (22 cases) meaningfully discussed how to overcome incumbency and their resistance to change (a gap in the broader literature as well[46]). The cases that did discuss this entry point indicate important reasons underlying incumbency and suggest ways to address them. Cases which feature sunk costs (like infrastructure and market structures that maintained an unsustainable status-quo) suggest facilitating economic reform as a critical way (Table 1; Figure 3), as in the case of Italy's National Recovery and Resilience Plan after the COVID-19 pandemic[25]. In other cases, resetting system rules and structures that constrain change are recommended in facing powerful vested interests (Table 1; Figure 3). An example from the food sector recommended that building networks and partnerships to facilitate knowledge exchange to help farmers specialising in grain can help overcome lock-ins and diversify production[24]. Navigating negative reactions (e.g., public backlash) is also suggested in some cases to address fear of negative impacts. For example, shutting down coal mines and power plants in India's energy sector created public concern about loss of income and increasing poverty, and so compensation and creating alternative livelihood opportunities for workers and communities were recommended to navigate negative reactions[26].

Leverage Positive Pressures. Many cases (33 cases) seek to leverage positive pressures by aligning everyday actions with the momentum of long-term goals and exogenous initiatives (e.g., policy frameworks, international commitments). Building collective and target-oriented efforts around purposeful, positive directions for the future may create windows of opportunity for catalysing innovation and phasing-out existing systems[47]. Cases seeking to promote low-carbon futures, sustainable development, and nature-positive action in particular benefit from harnessing this external momentum. For example, the UK's commitments to significant cuts in greenhouse gas emissions by 2030 created a window of opportunity that was leveraged by the UK Transition Plan Taskforce Implementation Guidance for accelerating net-zero transitions[27].
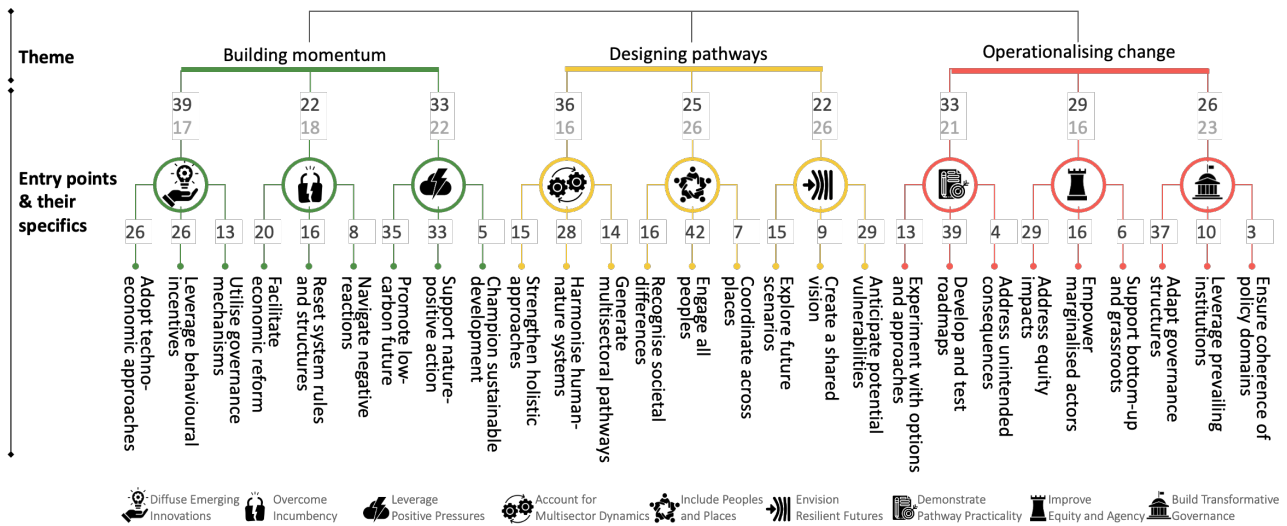
Figure 3. The frequency of 60 cases analysed across entry points. From the top, the first two numbers (i.e., black and grey colour) show the frequency of cases that directly (high relevance) or indirectly (moderate relevance) discuss each entry point. In the main text and in explaining the entry points, we only refer to the number of cases that directly discuss each entry point (the first black-colour number). From the top of the figure, the third number represents the frequency of the cases that discussed the specifics of entry points. One case can discuss multiple entry points, and each entry point can be discussed across multiple cases. Therefore, the numbers are not mutually exclusive and may not add up to the total number of 60 cases (Methods).

Designing pathways

Pathways, in the context of transitions, are sequences of changes or interventions that lead to more sustainable outcomes. We identified three entry points that aim to accelerate transitions by designing context-specific pathways that locate synergies across sectors and build robustness in the face of future uncertainty stemming from large-scale systemic shifts[48-50].

Account for Multisector Dynamics. This entry point is the most common in the context of designing pathways (36 cases). It refers to analysing key interlinkages and dependencies among sectors, their underlying causal drivers, and risk-benefit trade-offs[49]. Harmonising human-natural systems is the most common way for implementing this entry point across cases (Table 1; Figure 3). In one example, degrowth principles were integrated with dietary changes, and the estimated combined climate impacts were linked to the economy, society, and environment through modelling[31]. Other ways include strengthening holistic approaches to better understand the multi-dimensionality of transitions (e.g., how technology, people, and places interact in shaping public responses to new technologies in energy transitions[30]) and providing multisectoral solutions that can minimise trade-offs and maximise synergies (e.g., designing integrated strategies that increase food availability and limit emissions from land-use[32]).

Envision Resilient Futures. It is an entry point focused on designing pathways that attract progress whilst navigating potential shocks and stressors (22 cases). Like the gap in examples of overcoming incumbency, systematically addressing risk and uncertainty is another significant gap that we found across all cases. Among the cases that discussed risk and uncertainty, multiple ways are suggested such as creating a shared vision for change (e.g., stakeholder engagement and collective social learning to create a vision for food system transformations in Australia[34]), exploring future scenarios (e.g., what-if scenario analysis of the need for negative emission technologies under alternative pathways to a 1.5 degree climate future[33]), and anticipating potential vulnerabilities (e.g., locally-led climate action program in Kenya to adapt and ensure long-term resilience to climate-related vulnerability[35]).

Include Peoples and Places. This entry point (25 cases) speaks to the societal realities of geographical places and settings in which transitions emerge, so that accelerating transitions leads to viable, fair, and inclusive outcomes. Across cases, we found that the need for context-specific pathways is mostly achieved through engaging with people, like in co-design processes (Table 1; Figure 3). An example is the design of

7

SDG pathways in Bangladesh with a whole-of-society approach that aimed to include all stakeholders in context-appropriate ways[36]. Other ways, discussed to a lesser extent in our case studies, are about recognising societal differences (e.g., considering the role of behavioural and cultural factors as drivers of a circular economy[37]) and coordinating across places to improve pathways and connections between various locations and scales (e.g., coordinated national-to-industry level response for social protection of workers in agricultural transitions in Nigeria[38]).

Operationalising change

To enable acceleration in action, transitions need to be operationalised and support implementation needs across locations, sectors, and scales. We identified three entry points related to operationalisation, associated with the social learning and policy literature that emphasises the importance of evaluating practicality through experimentation, analysing, and addressing power and politics, and building transformative governance[14,51,52].

Demonstrate Pathway Practicality. Many cases (33 cases) seek this entry point to show feasibility and create legitimacy for operationalising change on the ground. They suggest different ways (Table 1; Figure 3). One is experimentation with options and approaches in key places, through which stakeholders learn how a pathway may unfold and its suitability. An example comes from rural USA, where local grassroots groups were supported and community design labs were developed to experiment with the idea of just transition from extractive to regenerative practices[39]. Developing and testing roadmaps to connect pathways to the desired outcomes via necessary investment (including fully costed business cases) and addressing unintended consequences that may arise during implementation are among other ways. The Towards a Just Transition Finance Roadmap in India is an example that outlined how India's financial system can support a just transition to mitigate socio-economic risk from climate change and the net-zero transition[26].

Improve Equity and Agency. Many cases (29 cases) also aim to foster human agency necessary to manage acceleration, navigate relationships among actors and power imbalances that can inadvertently lead to varied benefits across society, and act collectively on pathways to desired futures. Conflicting interests, uneven power dynamics, and unequal influence on outcomes are significant barriers to accelerating progress[53]. These cases focus on understanding who wins and who loses (i.e., equity impacts) and empowering marginalised groups (Table 1; Figure 3). For example, the Farm to Fork Strategy in Europe adopted an equity lens in addition to a healthy and environmentally friendly approach to food system transitions, designing tools like the Just Transition Fund to accelerate the transition towards climate neutrality by alleviating its socio-economic impact in the regions[41]. In a different context and at a more local scale, the Just Rural Transition in Indonesia offered mechanisms to help smallholders secure state-subsidised loans and multi-year purchasing agreements to facilitate a steady supply of income for farmers in food system transitions as a way of empowering marginalised actors[42]. Other ways we found include supporting and creating mechanisms for grassroots action and embedding bottom-up community stakeholder inputs in decision procedures[43].

Build Transformative Governance. The implementation of transitions is inherently political, and therefore requires careful consideration of governance and public policy[54] (26 cases). The most common ways we found in this entry point is about developing and adapting governance structures to suit the context, whether through transdisciplinary partnerships, centrally coordinated governance, or decentralised governance across society (Table 1; Figure 3). An example of innovative governance structures is seen in the Climate Change Mid-Century Strategy in Mexico, which envisioned two important bodies at the federal level to design and implement climate policy with coordination among government levels[45]. Other ways pertain to ensuring coherence of policy domains (i.e., breaking siloed structures of government, overcoming lack of incentives to work with other departments, and coordinating implementation of

pathways across branches of government and decision-making processes[6]) and leveraging prevailing institutions (i.e., integrating pathways within the existing institutions to support implementation[44]).

How context matters

While entry points focus on processes that span cases, important distinctions still arise between them in different contexts, indicating what each context can offer and opportunities for learning. Among various potential contextual factors, we analysed two that we specifically captured during the review of our cases: the effects of scale (i.e., global, national, local) and domain/focus on outcome (i.e., agriculture and food, energy and climate, justice and equity, sustainable development). We examined the prevalence of entry points across them (Methods).

Differences between scales

The cases feature transition efforts at global, international/national, and regional/local scales (20 cases each), and we found that these scales show affinity with different entry points. Global scientific assessments focus predominantly on diffusing emerging innovation to accelerate transitions (18 cases) and accounting for multisector dynamics (15 cases). Diffusing innovation in global scale cases is driven mostly by articulating immediate technoeconomic solutions but also increasingly through leveraging behavioural incentives (Figure 4b). This is evident, for instance, in a global assessment of the effects of consumption and production innovation (e.g., diet change, emissions pricing) on food system transitions[31]. Most of the model-based scientific analyses in the context of net-zero and sustainable development transitions are also among the multisector dynamics cases[28,33] (Figure 4a).

Cases of international and national strategies focus on operationalising change by seeking to demonstrate pathway practicality and build transformative governance for implementation (17 and 11 cases, respectively; Figure 4a). For example, the Sustainable Finance Action Council in Canada, which specified a detailed roadmap for implementing and scaling up climate investment for green transitions, is an example related to operationalisation at the national scale[55]. Cases of regional and local plans focus on designing transitions that include peoples and places (e.g., communities, businesses, and decision-makers in different localities) and map complex power relationships to improve equity and agency (11 and 14 cases, respectively; Figure 4a). The Ealing Transition Initiative in the UK is an example of both—co-development of a local plan with stakeholders and addressing community concerns about the loss of nature[56].
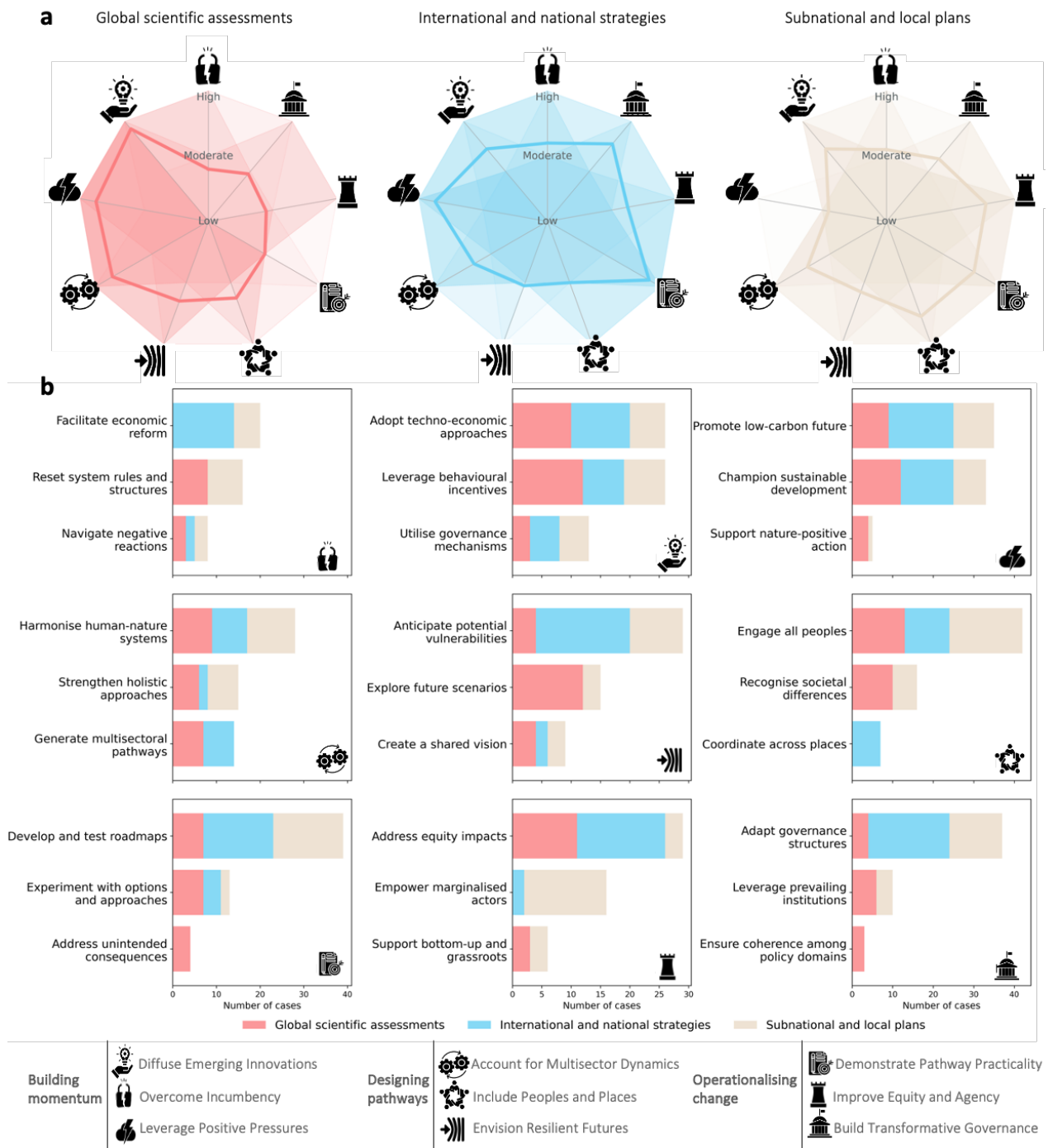
Figure 4. The spread of entry points across three scales. The differences emerged across cases through a context analysis (Methods). Spider diagrams (a) show the extent to which each entry point has been discussed across the cases at each scale, indicating strengths and gaps at the entry point level. Low, moderate, and high shows the relevancy of these cases to the entry point, meaning no, implicit, and explicit discussion, respectively (Methods). In the main text, we only refer to the number of cases that directly discuss each entry point (i.e., high relevancy). In each spider diagram, the shades represent the relevancy of cases in relation to each axis (i.e., entry point), and the thick line marks the average relevance of cases. The stacked bar charts (b) show the frequency of different specifics discussed in each entry point, indicating strengths and gaps at a more detailed level. In counting the case numbers in (b), one case can discuss multiple specifics, and there are cases that do not discuss any (i.e., low relevancy). Therefore, the summation of case numbers across bars in each subplot may be higher or lower than the total case number of 60.

Differences between domains

The effect of context in choosing entry points is even more evident across different transition domains (Figure 5). We found that in agriculture and food related transitions (total of 10 cases), transformative change is often considered primarily through novel technologies (i.e., diffuse emerging innovation) and in interaction with other parts of the economy (i.e., account for multisector dynamics) (6 and 5, respectively).

An example is a global inventory of 75 near-ready and future innovations, indicating the importance of integrated approaches across value chain stages[24]. Similarly, we found that transitions in the domain of energy and climate (17 cases) focus on the same two entry points, diffuse emerging innovation and account for multisector dynamics, more than other cases (13 and 10 cases, respectively). Innovation in energy and climate cases across these cases span technological (e.g., the diffusion of low-energy demand technologies[57]), social (e.g., strengthening education and public engagement for climate action[56]), and financial (e.g., incentivising decentralised energy generation[13]) areas.
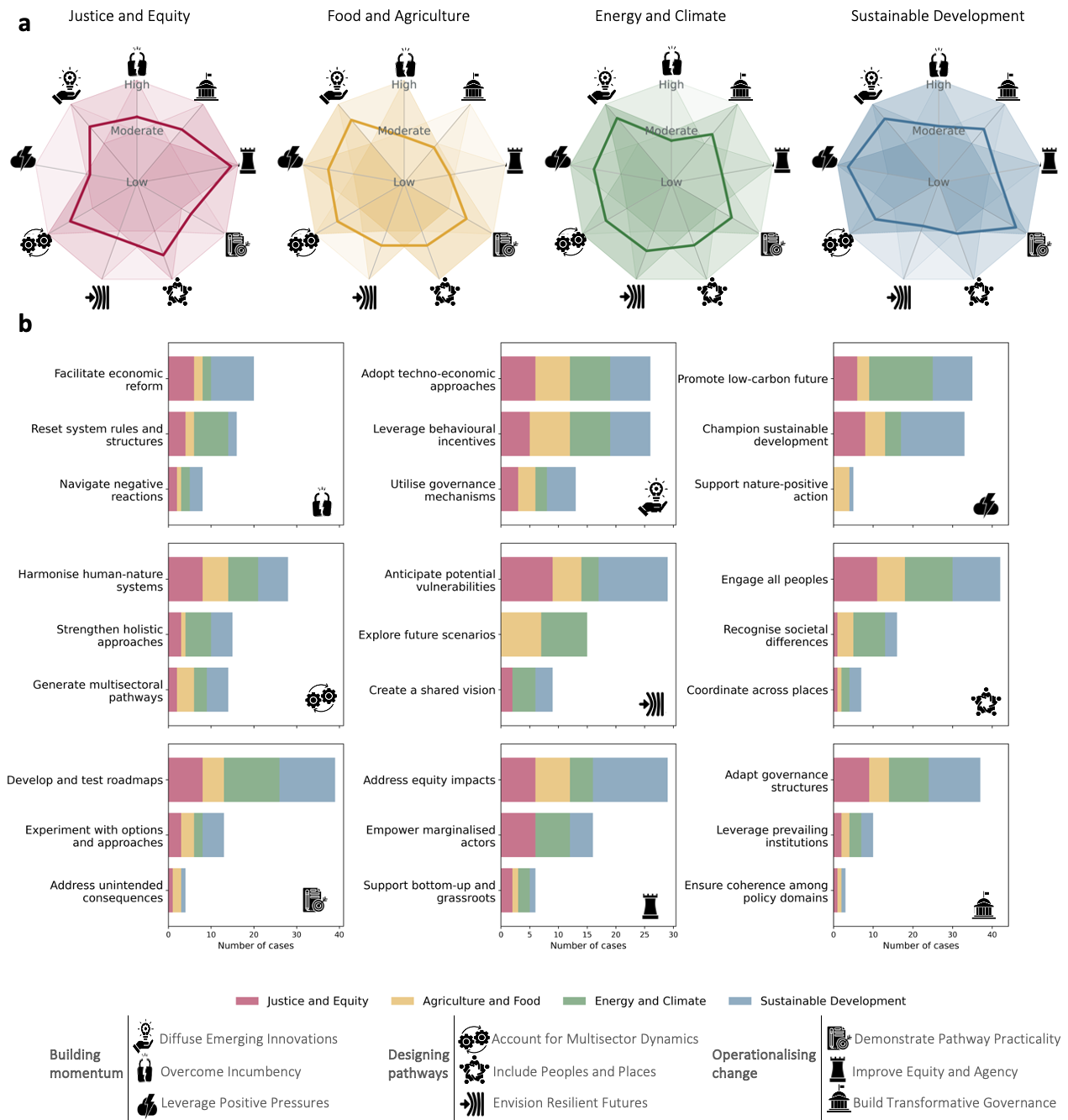
Figure 5. Differences in entry points across four domains. From the total of 60 cases, 14 are in justice and equity, 10 in agriculture and food, 17 in energy and climate, 19 in sustainable development. The differences emerged across cases through a context analysis (Methods). Spider diagrams (a) show the extent to which each entry point has been discussed across the cases at each domain. The stacked bar charts (b) show the frequency of different specifics for implementing entry points at each domain.

In contrast, the cases focused on justice and equity (total of 14 cases) and sustainable development (total of 19 cases) primarily suggest action points for operationalising change. The justice and equity cases often examine improving equity and agency in community-driven initiatives (12 cases). Adopting an equity lens

assists in understanding unintended consequences (e.g., how the clean energy transition is negatively affecting households[58]) and seeks to empower marginalised actors (e.g., supporting small farmers and landless youth through skill development and start-up capital activities in Pakistan[59]). Demonstrating pathway practicality (14 cases) also provides a means to operationalise change in the sustainable development cases, for example, through developing and testing roadmaps (e.g., rehabilitation planning for coal mines in Australia's Latrobe Valley[44]).

Engines of change

Across the cases analysed, we identified three recurring, deliberate combinations of entry points that create reinforcing loops and virtuous cycles between different processes with complementary insights for accelerating transition (Methods). We called them e*ngines* of change (Figure 6).

The green economy engine

The green economy engine, observed in 9 cases, accelerates transitions through top-down change (e.g., government-led structural reforms in the economy), induced and guided by influences from international pressure (e.g., Paris agreement, SDGs). In our cases, we found that this engine often originates from growing urgency and commitment among policymakers to respond to challenges such as climate change, resource-intensive development, and inequity (i.e., leverage positive pressures). The need to respond is addressed through compelling direction and a political agenda of reform (i.e., overcome incumbency), and a broader economic reform that creates a window for innovation (e.g., financial[55], technological[3], and political and social [58]) to emerge and spread (i.e., diffuse emerging innovation).

The green economy engine appeared predominantly in international and national strategies (6 out of 9 cases). The clearest examples are from the Green Fiscal Incentives Policy Framework of Kenya where government interventions stimulated shifts in production, consumption, and investment[35] and the European Sustainability Transitions Policy and Practice where economy-wide policy mixes were aimed at innovation and structural economic change[59] (Figure 6a).

The system resilience engine

The system resilience engine, seen in 11 cases, accelerates change through synergies linking multiple sustainability dimensions and by building adaptive capacity within communities to respond to disruption (Figure 6b). The system resilience engine in our cases often starts with a recognition that transitions can result in complex changes with potentially significant trade-offs and externalities (e.g., energy and climate transition impacts on short-term job losses and the livelihood of communities). In the cases related to this engine, complexity indicates the need for holistic approaches, acknowledging the systems-level interlinkages that create vulnerabilities and considering various global, national, and local aspirations that communities envision for their future (i.e., account for multisector dynamics). The complexity also necessitates the ability, in these cases, to engage with people in their communities (i.e., include people and places) to adjust to future disruptions and shocks, maintaining resilience, whilst realising future visions (i.e., envision resilient futures). Complexities, risks, and vulnerabilities are often place-based (e.g., drought, flood, job loss), and the resources (e.g., money, skills, natural resources) to address them differed across cases.

We observed the system resilience engine mostly in subnational and local plans (7 out of 11 cases). An example of this engine is in the rural just transition case of the Golden Agri-Resources program in Indonesia that sought to build community resilience and tackle poverty through community-conservation partnerships and improved infrastructure. In this case, dependence on aging, lower yield palm oil plants, further impacted by climate change, posed acute livelihood risks for smallholders and forced them to expand their planting area, resulting in subsequent pressure elsewhere such as on forest ecosystems[42].

The equitable action engine

The equitable action engine, seen in 21 cases, arises from the need for fair and equitable transitions and is progressed through a cycle of planning, enacting, and implementation (Figure 6c). In the cases analysed, this engine often germinates from efforts associated with operationalisation. This includes formulating goals and identifying actions through planning (i.e., demonstrate pathway practicality) as well as establishing suitable governance structures for purposeful enactment and administration of the 'how' and 'when' of on the ground action (i.e., build transformative governance). The cases associated with this engine address situations in which some people gain more (or lose more) than others through transitions, creating power imbalances with enduring inequity effects and hampering operationalisation (i.e., improve equity and agency). To address this, these cases seek to empower marginalised actors by promoting more inclusive decision-making process[60], creating decent work opportunities[61], or offering compensation to those negatively impacted[58].

We identified the equitable action engine mostly in international and national strategies (13 out of 21 cases). One example from the Bangladesh Voluntary National Reviews suggested projects, programmes, and policies, with a 'whole of society' approach that enagaged diverse stakeholders to achieve SDGs by 2030[36]. There are also several examples from subnational and local plans featuring this engine (8 out of 21 cases). The Tanmil Nadu Rural Transformation Project in India, a subnational example, provided a comprehensive procurement plan to reduce poverty through business development and local employment, with clear governance to guide rural enterprises[62].
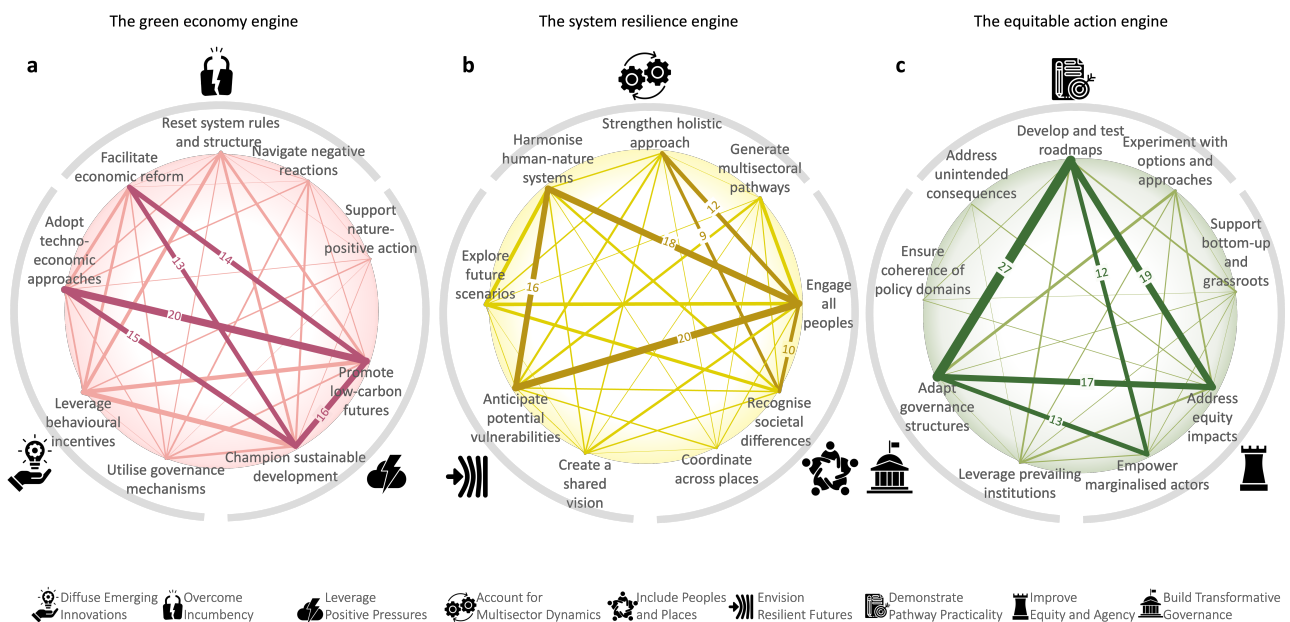
Figure 6. **Patterns of interactions between entry points (i.e., engines of change).** Each engine includes a set of entry points. The engines emerged based on the similarity of interactions between entry points across cases. See interaction analysis in Methods for details. In each engine, entry point is represented by an arc and icon and their specifics are represented by a point around the circle. The lines between the entry points represent the cases with interactions. The size of the lines is proportional to the number of cases, also annotated in small number only for major interactions in each engine.

Discussion and conclusions

Lessons learnt

We learnt two broader insights from the results. First, the analysis of 60 cases showed multiple valid entry points to sustainability transitions. This was supported by multidisciplinary thinking from different fields

which reflect unique (yet sometimes overlapping) understandings that compete in the process of far-reaching change. This diversity of entry points identified indicated the importance of not homogenising our understanding of transition acceleration and acknowledging the plurality of views and standpoints, which is essential for transdisciplinary research. We showed how the prevalence of these various entry points can be influenced (knowingly or unknowingly) by different contexts of the problem at hand (i.e., domain of transition, spatial scale), highlighting what has been used previously in a certain context and succeeded (for making decisions about implementing in future transition cases) as well as for identifying gaps in different contexts. There are also a range of other factors, beyond the scope of this paper and for future research, such as ambition and motivations, values and preferences of actors, availability of resources (e.g., data, expertise), and the underlying conditions (e.g., institutional factors, historical development), that could influence different ways of thinking about accelerating transitions and could increase or diminish opportunities for the prevalence of different entry points.

Second, looking at feedback loops between entry points through different patterns of interactions (i.e., engines) enabled us to understand how different ways of thinking about transitions can interact and create virtuous cycles. In accordance with other studies[22], our analysis showed that acceleration requires a move away from individual approaches to a targeted combination of complementary approaches to support change. So far, we have identified three engines that represent some of these important interactions in our selected cases. But it is expected that further analysis with a broader body of data may reveal more patterns of interactions which warrant future investigation.

Implications for policy and practice

What we learnt through this paper has three main implications for policymakers and people engaged in changemaking efforts and how they can understand, evaluate, and advance transition acceleration.

First, differences in entry points across contexts indicate unique insights that each domain or scale has to offer, and therefore opportunities for learning that can be transferred to address complex challenges prevalent in other transitions. For example, we noticed through our analysis that at a national scale, accelerating transitions often adopt top-down governance endeavours that provide guidance and facilitate coordination and support across policy domains. Although essential, they are insufficient for conditions that are unique to each subnational region and community. This indicates an opportunity for learning from the transition experiences at local scale where changemaking efforts are better supported by engaging with societal actors and empowering them to shape their own sustainable transitions[63]. We observed similar learnings that can be discussed between various domains of transition. An example is a transition that the food and agriculture domain can learn from other domains to empower food actors (e.g., farmers, workers, consumers) equitably in the change-making process[64]. This can include learning from multiple equity lenses in the broader sustainable development domain to better consider complexities that may arise from historical (e.g., colonial) legacies as well as difficulties around ongoing equitable transition processes and their outcomes[65]. The vision for accelerating systemic change aided by connecting and coordinating insights across different areas indicates the need for an integrated learning system and knowledge network, comprised of scientists, policy and government, industry, and communities, that can synthesise, compare, and share the experiences, needs, and approaches to what works from multiple lenses rooted in different worldviews, perspectives, and knowledge sources[66].

Second, beyond the appreciation of diverse knowledge, the effective implementation of a diversity of entry points in action necessiates the establishment of certain foundational conditions within each context. One of them is the initiation of the required agency for contributing to what is needed for acceleration on the ground. While not explicitly addressed in our analysis, we observed a spectrum of organisations with different roles throughout the various stage of transitions. For example, in the green economy engine,

governments took the position of catalysts, making commitments for economic reform to tackle sustainability challenges while science and industry actors led the development of innovative solutions to these challenges. Subsequently, governments made decisions, choosing among and supporting suitable options. This pattern underscores the need for transition actors to explicitly co-define agency for change and collaboratively delineate their respective roles, thereby fostering acceleration through interdisciplinary collaboration and democratic leadership.

Third, the successful activation of entry points is also contingent upon the existence of appropriate structural configurations (e.g., partnerships, funding mechanisms) and institutional arrangements (e.g., regulations, protocols) to provide the required conditions within each context[22]. For example, our observation, though not detailed in our analysis, was that the system resilience and equitable action engines contributed primarily to intermediary structures that help communities build resilience and adaptive capability (e.g., an international funding body to promote rural economic transition in Pakistan[67]). They were also primarily supported by governing insitutions that can ensure a equitable distributions of funds and rescources (e.g., a multi-year purchasing agreement with smallholders to support rural agricultural transitions in Indonesia[42]). While some of these structures and instituions might exist and can be reoriented in some places, they may need to be deliberately built or re-oriented to support transitions in other places, given existing political and governance circumstances and different ideas and values that transition may imply in each place.

The entry points and their interactions presented in this paper outlined a set of practical directions for transition acceleration from research and action, echoing the important message of 'taking diverse knowledges seriously'[22]. They can offer guidance for enhancing flexibility and deliberative reflection on diverse perspectives in planning processes and supporting strategic decision-making in projects and applications. They can be useful for researchers, practitioners, and policymakers to understand the growing diversity of approaches but also to offer guidance on what collaborative, multi-stakeholder efforts should concentrate on for making context-appropriate selections. The entry points, however, should not be taken as definitive, but as a means to foster robust dialogue among people from diverse disciplines and perspectives. They should be used to enable different views to deliberate about the nature and form of sustainability outcomes they want to achieve, how they transition, and the choices that are most suitable for their context.

Acknowledgement

Methods

Transition definitions and concepts

Transition represents a broad topic featuring many alternative definitions and concepts, underpinned by different theories. Before the selection and empirical analysis of the cases, we reviewed definitions and concepts from multiple areas of research to clarify our position in this broad area. It included *definitions* about what we mean by transition (i.e., a reference point that later guided the selection of the cases) and a set of *concepts* that represent diverse and multidisciplinary thinking about transitions (i.e., dimensions that later helped know what to learn across cases).

Definitions. Transition as a way of thinking and a field of research emerged in 1990s[68]. It was originally defined in socio-technical system research as "long-term, multi-dimensional, and fundamental transformation processes through which established socio-technical systems shift to more sustainable modes of production and consumption"[69]. There are other terms associated with transition that are used frequently (and in most cases interchangeably) in scientific and policy literature. An example is *transformation* which has been defined as "fundamental changes in structural, functional, relational, and cognitive aspects of socio-technical-ecological systems that lead to new patterns of interactions and outcomes"[22] (among many other definitions[11]). Transformation is contrasted with transition in some contexts as the outcome of the fundamental shift and the resulting reconfiguration of systems[3], but in other contexts is discussed as a duality which provides complementarities in terms of how to describe, interpret and support desirable radical and non-linear societal change[11]. *Pathway*, another term associated with transition, is often used in socio-technical system research to describe alternative patterns through which a transition may emerge[70] or as the elaboration of social-economic-political and environmental trajectories to achieve desired futures in the socio-ecological system research[71]. The same term pathway has been also used slightly differently in adaptive planning[72] and development studies[73] as alternative possible trajectories for knowledge, intervention, and change, which prioritise different goals, values and functions. *Systemic (systems) change* is another term used in relation to transition in broader sustainability science to describe complementary shifts that cut across multiple systems and should be coherently pursued to form a transition away from currently established to emerging (and more sustainable) systems[8]. While these terms have overlaps and are not entirely independent of one another, they represent how transition is conceived in different fields of research and by various underlying theories[11].

We adopted a flexible and broader definition of transition in this paper, which is inclusive of other similar terms across different areas. We defined transition as *pervasive change* for *persistent problems*[74]. Persistent problems are the negative side-effects (e.g., food insecurity, soil degradation) of existing systems. Pervasive change is the confluence of developments across sectors and scales of the economy that creates a large-scale, nonlinear, and disruptive change to address these problems. This broad definition was used as a reference point to guide the selection of relevant cases.

Concepts. Transition also features concepts related to enabling and accelerating change that cut across the boundaries of research areas, theories, methods, and applications[75]. From previous reviews[69,75], we identified important concepts (highlighted in italics in the next three paragraphs) that were recurring in the literature.

The first set of concepts was related to understanding the dynamics of accelerating change, drawn from socio-technical transitions studies[75] and sustainability science[76]. These concepts corresponded to structural approaches proposed in Scoones, et al. [22]. Some studies discussed how transitions emerge in various forms and speeds[70], through different maturation stages[9], and with a mix of incremental changes (e.g., technology improvement) and fundamental shifts (e.g., post-growth development). They suggested an understanding of dynamics and the different *inertia* and *change* mechanisms over time to enable leverage points and accelerate change. Similar terms were used in other areas of literature when referring to the same concepts, for example, path-dependency, lock-in, and resistance[77,78] refer to what we called inertia and social tipping points, technological innovation, and system leverage points in association with what we called change[8,13]. Studies also discussed how transitions co-evolve from a combination of purposefully designed and emergent pathways that need to be guided and navigated to possible future states[9]. Hence, understanding transitions should include *directionality* and normative orientation[79]. Sustainability through different policy frameworks (e.g., SDGs, Paris Agreement) had an important role in designing normative directions and shaping the emergence and behaviour of transition pathways[6].

The second set of concepts, corresponding to systemic approaches in Scoones, et al. [22], was related to designing transitions from a combination of deliberate and emergent pathways towards potential future

states, drawn from the literature around integrated assessment[80], multisector dynamics[49] and sustainability science[76]. Some studies discussed how designing transitions should be sensitive to the *complexity* of change and carefully leverage interactions between various dimensions of transitions and their positive or negative side-effects to accelerate change[49]. They refer to this complexity through other similar concepts such as trade-offs and synergies in sustainability science[76], sectoral integrations in the field of multisector dynamics[49], and integrated human-natural systems in integrated assessment research[33]. It was acknowledged in the literature that the more complex systemic changes are, the more they become exposed to *uncertainty* and novel risks that can disrupt transformation[81]. To manage these uncertainties, it was suggested that transitions be designed in a way that can better anticipate uncertainty and adapt and adjust regularly to ensure robustness and resilience against short-term risks and long-term vulnerabilities[82]. Studies also recognised that there is no one-size-fits-all approach in designing transitions as they can vary across context, which highlights the importance of civil society, social movements, and cultural change[83]. There was an increasing focus on understanding *settings* (e.g., actor behaviour, values, preferences, disagreements, resources, institutional settings) to capture the social realities of places and peoples in which change occurs[84].

The third set of concepts, corresponding to enabling approaches in Scoones, et al. [22], was related to implementing transitions on the ground and efforts that support their wider rollout across locations, sectors, and scales, drawn from governance and policy literature[14,54,85]. Some studies discussed *practice* through needs to lay out plans that can articulate implementation in a step-by-step process. As such, they highlighted the importance of transitions that are feasible in the socio-cultural, eco-political, and technological settings of their surrounding environment[86] and are embedded in decision processes in which they operate. Studies acknowledged that the effects of transitions can inadvertently vary across context, creating 'losers' and 'winners' in different regions[54]. They suggested that addressing disparate outcomes requires an understanding of *power* (e.g., conflicts and cooperation between actors) and politics in implementing transitions. Transitions were also discussed as inherently political processes that require *governance* arrangements for deciding and acting on what is needed to instigate and realise change[14,85].

The objective here was not to provide a comprehensive review of the full body of literature on transition, but rather to highlight the breadth of key concepts and their purposes to be used as our analytical lens in the content review and for extracting insights from the selected cases. The selected transition concepts drawn from different areas of literature were agnostic to a particular field, theory, or sectoral domain, and hence represented multidisciplinary thinking about transition. We used these concepts later as our lens to review and code the selected cases.

Case selection

We chose a balanced mix of cases from both scientific and grey (i.e., policy and practice) literatures, with a range of global, national, and local scales. This diversity and the differences between these cases required us to use a hybrid (systematic and integrative) search process for case selection, suitable for each scientific and grey literature. Hybrid searches often seek to address the inherent limitation of one search approach with another search approach[87] and have been used in previous research[66,88].

Scientific literature search. To identify cases related global scientific assessments, we used a systematic search in Web of Science because it is a reliable search approach and the database covers a diverse range of journals related to sustainability transition topics. We limited our search to recent peer-reviewed publications that appeared post UN SDGs and the Paris Agreement i.e., 2015 or later. To search systematically, we identified a range of preliminary keywords and tested search strings to scope the diversity of related documents being captured. The following query was eventually used with appropriate adjustments to the Boolean operators: ((TI=((transition* OR transformat*) AND (net?zero OR emission*

OR climate?change OR sustainabil* OR biodiversity))) OR AB=((transition* OR transformat*) AND (net?zero OR emission* OR climate?change OR sustainabil* OR biodiversity))) OR AK=((transition* OR transformat*) AND (net?zero OR emission* OR climate?change OR sustainabil* OR biodiversity)). This resulted in an initial 66,640 documents. We used exclusion operators to avoid papers with a focus on, for example, understanding phase 'transition' in lithium batteries. The exclusion operators included: (1) papers that perform in the top 1% based on the number of citations received when compared to other papers published in the same field in the same year (a metric unbiased to publication year), (2) selected journals that discuss transition/transformation in a broader sustainability context, (3) papers that are at a global scale, and (4) papers that discuss transition in a non-theoretical way, so that insights we that find could be empirical and transferrable to other contexts. This filtering returned 113 documents, from which we retained 20 documents of highly relevant cases to transition after an initial screening of abstracts (Supplementary Data 2).

Grey literature search. The search approach was different in the grey literature, given that these documents were quite diverse and recorded in reports, government documents, and websites. They were siloed in various departments with different priorities. Hence, the word transition or transformation was often lost, and documents became simply, 'clean energy plans' (for example), even though they included important insights relevant to transition. Some countries had a transition ministry (e.g., France's Ministry of Ecological Transition), some had set up special panels (UK's Transition Plan Task Force), and others had transition goals and strategies included in their national plan (e.g., Italy's National Recovery and Resilience Plan). Given this inconsistency and diversity, we did not systematically search all the documents from the database searches, but rather we performed an integrative search[89] with focus on selected documents that at least minimally included transition concepts and had enough diversity in terms of a balance between locations (i.e., Global South/North, East/West) and sectoral focus.

To identify cases related to international and national strategies, we used Google as the search engine and adopted the following generic keywords to find relevant documents: "sustainability transition" and "sustainability transformation". The word "government" was added to refine the search and seek official documents. Occasionally, a snowball search was undertaken from websites found within the Google search. We included webpages and reports in English, French, Italian, Spanish, and Portuguese, as our co-authors were able to read in these languages. The first round of search focused on high-income countries as they are often the major contributors to sustainability problems and have a higher level of resources and capabilities for transitions. In the second round, we included low- and middle-income countries with choices diverse enough to represent various geographical locations. Finally, we selected and downloaded three to five reports or internet pages for each country. From this pool, we selected two additional complete documents for each county, and one co-author chose one of those two documents for analysis. A few reports from international organisations suggested by co-authors were highly relevant, and so were added to this final list of cases manually, resulting in a total of 20 documents at the (inter)national scale (Supplementary Data 2).

Cases related to subnational and local plans were mainly restricted to websites, and much of the organising occurred on social media platforms (particularly Facebook). Some of the information was ephemeral with websites which were no longer maintained or lapsed registration. Given these limitations, we used Google search with a very broad set of search strings for "local transition" or "local transformation", followed up with snowball searches based on initial search results. In this search process we discovered that individual, local-scale initiatives were frequently part of a larger network of transition initiatives. Hence, multiple cases were often included in one initiative. To some degree, this means that local scale initiatives were frequently "general sustainable development" plans, and the focus was either tailored to the local conditions or sought to be all-embracing of transition (e.g., energy, food systems, plastic waste). Utilising the same principle of diversity in terms of a balance between locations (i.e., Global South/North, East/West, developed/developing) and domain focus, one co-author initially selected 31 initiatives. Another co-author

then chose 20 of these initiatives for diversity and relevance to transition in subnational and local scale (Supplementary Data 2).

In-depth review and coding

We reviewed the contents of the selected cases in detail and analysed to what extent and in what way each case, directly or indirectly, discussed any of the transition concepts identified from the literature. We analysed the case discussion of each transition concept using a coding procedure that: (a) assigned three subjective levels of relevancy to indicate the extent to which the case discussed the concept (i.e., 0 for low, 1 for moderate, and 2 or high referred to no, implicit, and explicit discussion, respectively); (b) provided an insight (by referring to the exact text in case documents) to explain in what way the case talked about the concept. To implement this coding procedure, three primary co-authors initially reviewed all cases and specified their relevancy levels and insights in relation to each concept (Supplementary Data 3). We acknowledged that the coding is a subjective process, and depends on the analyst's judgment. To mitigate the risk of biases in this subjective coding procedure, a secondary co-author reviewed all the cases independently and flagged those that could be coded differently for further deliberation and modification by the primary co-authors.

Clustering

The analysis of cases in relation to different transition concepts resulted in a significant diversity of insights (60 cases coded under 9 concepts). Despite differences between cases, there were similarities and recurring processes in the coded materials that indicated an opportunity for clustering. We performed a qualitative clustering to identify these recurring processes, which we labelled entry points. Clustering can be performed computationally or manually, but we chose to do it manually and qualitatively in this research to ensure we captured the nuances of many different approaches to accelerating transition.

First, three primary co-authors simplified all the coded materials (Supplementary Data 3) and created shortened insights that were more specific and intuitive for qualitative clustering (Supplementary Data 3). A secondary co-author then grouped all the shortened insights based on their similarity in two hierarchical steps of entry points (as general processes) and their specifics (as the context-specific means of implementation). This was a fully iterative process where the shortened insights were grouped and regrouped several times to minimises the variance within each entry point whilst maximising the meaningful difference between different entry points (a standard balance often sought in other clustering examples[66,88]). Eventually the clustering of coded materials from cases resulted in a set of 9 entry points, each with 3 specific means of implementation (Supplementary Data 4). Despite efforts to maintain this balance, we acknowledge that the distinction between entry points is not always clear-cut (which is an inherent feature of clustering). For instance, multiple entry points talked about policy and governance, but each from a different perspective and for a different purpose.

Context and interaction analyses

We extracted the properties of each case in relation to scale and domain to identify similarities and differences among entry points across contexts (Supplementary Data 4). We categorised the cases into the three scales: global scientific assessments, international and national strategies, and subnational and local plans. The decision to place each case in each scale of analysis was based on what the focus of each report was. For example, if transition was mostly discussed in the context of communities, cities, and rural areas, we placed it under subnational and local plans.

We also categorised cases into four domains based on their focus on outcome, either sectoral outcomes like 'agriculture and food' and 'energy and climate', or societal impacts concerning 'justice and equity' and broader 'sustainable development'. The classification process based on domain faced two primary challenges. Initially, the dilemma was whether to consolidate various sectoral and societal outcomes into singular domains or to keep them separated—for instance, merging energy and climate. Starting with many potential categories (e.g., decarbonisation, energy transition, and circular economy, biodiversity conservation, urban transition), we realised that a larger number of sectoral/societal outcomes resulted in less cases in each and a highly uneven number of cases across these foci on outcomes (e.g., circular economy had only one relevant case whereas energy transition had nine cases). This impeded robust and comparable conclusions about transition in each and across domains. Consequently, we decided to merge sectoral/societal outcomes into four broad domains with a similarity of what they focus on to enhance the meaningfulness of our conclusions and ensure a balanced distribution of cases across them. Once we decided about the number of domains, the second challenge involved the assignment of cases to a single or multiple domains, a task complicated by the multifaceted nature of the cases, often spanning multiple outcomes (e.g., an energy transition case that also focuses on justice and equity). While we acknowledged multiple aspects that each case has, we decided to assign the case to only one domain that was central to the case to improve the clarity of analytical process.

After deciding about the number of scales/domains and assigning cases to them, we mapped the relevancy level of each case (i.e., 0 or low, 1 or moderate, and 2 or high to refer to no, implicit, and explicit discussion) to the entry points across scales/domains in a spider diagram. This was represented with shades of colour in Figure 4a/Figure 5a. To better demonstrate the patterns across scales, we also mapped the average of relevancy level for entry points across all cases at each scale/domain (thick line in Figure 4a/Figure 5a).

We also analysed interactions between entry points. By generalising from case-specific findings, we specified whether each case could be related to single or multiple entry points to highlight the reinforcing interactions (Supplementary Data 5). This interaction analysis approach, has been also previously used in other contexts (e.g., the build-up and acceleration of innovation systems[90]).

References

1   Rockström, J. *et al.* Safe and just Earth system boundaries. *Nature* (2023).
2   Markard, J., Geels, F. W. & Raven, R. Challenges in the acceleration of sustainability transitions. *Environmental Research Letters* (2020).
3   Denton, F. *et al.* Accelerating the Transition in the Context of Sustainable Development. (Cambridge University Press, Cambridge, UK and New York, NY, USA, 2022).
4   Stirling, A. Keep it complex. *Nature* **468**, 1029-1031 (2010).
5   Rockström, J. *et al.* The planetary commons: A new paradigm for safeguarding Earth-regulating systems in the Anthropocene. *PNAS* **121**, e2301531121 (2024).
6   Sachs, J. D. *et al.* Six Transformations to achieve the Sustainable Development Goals. *Nat. Sustain.* **2**, 805-814 (2019).
7   Geels, F. W., Sovacool, B. K., Schwanen, T. & Sorrell, S. Sociotechnical transitions for deep decarbonization. *Science* **357**, 1242-1244 (2017).
8   Moallemi, E. A. *et al.* Early systems change necessary for catalyzing long-term sustainability in a post-2030 agenda. *One Earth* **5**, 1–20 (2022).
9   Rotmans, J., Kemp, R. & Asselt, M. v. More evolution than revolution: transition management in public policy. *Foresight* **3**, 15-31 (2001).
10   Olsson, P., Galaz, V. & Boonstra, W. J. Sustainability transformations: a resilience perspective. *Ecol. Soc.* **19** (2014).
11   Hölscher, K., Wittmayer, J. M. & Loorbach, D. Transition versus transformation: What's the difference? *Environmental Innovation and Societal Transitions* **27**, 1-3 (2018).
12   Allen, C. & Malekpour, S. Unlocking and accelerating transformations to the SDGs: a review of existing knowledge. *Sustainability Science* **18**, 1939-1960 (2023).
13   Otto, I. M. *et al.* Social tipping dynamics for stabilizing Earth's climate by 2050. *PNAS* **117**, 2354 (2020).
14   Kern, F. & Rogge, K. S. Harnessing theories of the policy process for analysing the politics of sustainability transitions: A critical survey. *Environmental Innovation and Societal Transitions* **27**, 102-117 (2018).
15   Andersen, A. D., Markard, J., Bauknecht, D. & Korpås, M. Architectural change in accelerating transitions: Actor preferences, system architectures, and flexibility technologies in the German energy transition. *Energy Res. Soc. Sci.* **97**, 102945 (2023).
16   von Braun, J., Afsana, K., Fresco, L. O. & Hassan, M. H. A. *Science and Innovations for Food Systems Transformation*. (Springer Cham, 2023).
17   Independent Group of Scientists appointed by the Secretary-General. Global Sustainable Development Report 2023: Times of crisis, times of change: Science for accelerating transformations to sustainable development. (United Nations, New York, 2023).
18   Coenen, L., Benneworth, P. & Truffer, B. Toward a spatial perspective on sustainability transitions. *Res. Pol.* **41**, 968-979 (2012).
19   Kikstra, J. S. *et al.* The IPCC Sixth Assessment Report WGIII climate assessment of mitigation pathways: from emissions to global temperatures. *EGUsphere* **2022**, 1-55 (2022).
20   UN. Global Sustainable Development Report 2023: Times of crisis, times of change: Science for accelerating transformations to sustainable development. (United Nations, New York, 2023).
21   Moallemi, E. A. *et al.* Shortcuts for accelerating food system transitions. *One Earth* (2024).
22   Scoones, I. *et al.* Transformations to sustainability: combining structural, systemic and enabling approaches. *Curr. Opin. Env. Sust.* **42**, 65-75 (2020).
23   CEE Bankwatch Network. Local community participation in the Transformation Action Plan for the Slovakia's Upper Nitra Coal Region (2019).
24   Herrero, M. *et al.* Innovation can accelerate the transition towards a sustainable food system. *Nat. Food.* **1**, 266-272 (2020).
25   Domani, I. Piano Nazionale di Ripresa e Resilienza (PNRR). (2021).
26   CDC. Towards a Just Transition Finance Roadmap for India: Laying the foundations for practical action. (British International Investment, 2021).
27   TPT. Transition Plan Taskforce Implementation Guidance. (The Transition Plan Taskforce, UK, 2023).
28   Leclère, D. *et al.* Bending the curve of terrestrial biodiversity needs an integrated strategy. *Nature* **585**, 551–556 (2020).
29   UNDP. Ethiopia 2030: A Country Transformed? Options for A Next Generation of Reforms. (United Nations Development Programme, 2022).
30   Boudet, H. S. Public perceptions of and responses to new energy technologies. *Nature Energy* **4**, 446-455 (2019).

31   Bodirsky, B. L. *et al.* Integrating degrowth and efficiency perspectives enables an emission-neutral food system by 2100. *Nat. Food.* **3**, 341-+ (2022).

32   Leclere, D. *et al.* Bending the curve of terrestrial biodiversity needs an integrated strategy. *Nature* **585**, 551-+ (2020).

33   van Vuuren, D. P. *et al.* Alternative pathways to the 1.5 degrees C target reduce the need for negative emission technologies. *Nat. Clim. Change.* **8**, 391-+ (2018).

34   CSIRO Futures. Reshaping Australian Food Systems – A Roadmap towards a more sustainable, productive and resilient future for Australia's food,. (CSIRO, Canberra, 2023).

35   Government of Kenya. The Green Fiscal Incentives Policy Framework (Draft). (The National Treasury and Planning Directorate of Budget Fiscal And Economic Affairs Financial and Sectoral Affairs Department, Kenya, 2022).

36   Government of the People's Republic of Bangladesh. Bangladesh Voluntary National Reviews (VNRs) 2020 Accelerated action and transformative pathways: realizing the decade of action and delivery for sustainable development. (Bangladesh, 2020).

37   Muscat, A. *et al.* Principles, drivers and opportunities of a circular bioeconomy. *Nat. Food.* **2**, 561-566 (2021).

38   Uyi Ojo, G. & Mustapha, H. Just Transition in Nigeria: Case of Agriculture and Petroleum Sectors. (Nigeria Labour Congress, 2019).

39   Transition US. Regeneration Nation. (Transition US, USA, 2022).

40   Davis, K. F. *et al.* Meeting future food demand with current agricultural resources. *Global Environmental Change-Human and Policy Dimensions* **39**, 125-132 (2016).

41   European Commission. Farm to Fork Strategy: For a fair, healthy and environmentally-friendly food system. (2020).

42   Just Rural Transition. Golden Agri-Resources: Rejuvenating Farmer Incomes through Finance. (Indonesia, 2021).

43   Asian Development Bank. Toward mainstreaming and sustaining community-driven development in Indonesia. (2016).

44   DJPR. Latrobe Valley Regional Rehabilitation Strategy. (Department of Jobs, Precincts and Regions, State Government of Victoria, Melbourne, Australia, 2023).

45   SEMARNAT-INECC. Mexico's Climate Change Mid-Century Strategy. (Ministry of Environment and Natural Resources (SEMARNAT) and National Institute of Ecology and Climate Change (INECC), Mexico City, 2016).

46   Turnheim, B. & Geels, F. W. The destabilisation of existing regimes: Confronting a multi-dimensional framework with a case study of the British coal industry (1913–1967). *Res. Pol.* **42**, 1749– 1767 (2013).

47   Carrard, N. Reorienting water and sanitation narratives towards sustainability transformations. *Nature Water* **2**, 2-3 (2024).

48   Trutnevyte, E. *et al.* Societal Transformations in Models for Energy and Climate Policy: The Ambitious Next Step. *One Earth* **1**, 423-433 (2019).

49   Reed, P. M. *et al.* Multisector Dynamics: Advancing the Science of Complex Adaptive Human-Earth Systems. *Earth's Future* **10**, e2021EF002621 (2022).

50   Guivarch, C. *et al.* Using large ensembles of climate change mitigation scenarios for robust insights. *Nat. Clim. Change.* **12**, 428-435 (2022).

51   Avelino, F. Theories of power and social change. Power contestations and their implications for research on social change and innovation. *Journal of Political Power* **14**, 425-448 (2021).

52   Raven, R., Kern, F., Verhees, B. & Smith, A. Niche construction and empowerment through socio-political work. A meta-analysis of six low-carbon technology cases. *Environmental Innovation and Societal Transitions* **18**, 164-180 (2016).

53   Weitz, N., Carlsen, H., Bennich, T., Nilsson, M. & Persson, Å. Returning to core principles to advance the 2030 Agenda. *Nat. Sustain.* **6**, 1145-1148 (2023).

54   Avelino, F. Power in Sustainability Transitions: Analysing power and (dis)empowerment in transformative change towards sustainability. *Environmental Policy and Governance* **27**, 505-520 (2017).

55   SFSC. Taxonomy Roadmap Report: Mobilizing Finance for Sustainable Growth by Defining Green and Transition Investments. (Sustainable Finance Action Council and the Government of Canada, 2022).

56   Ealing Transition Initiative. Ealing Climate and Environmental Emergency: A community response. (The Ealing Council, Ealing, UK, 2019).

57   Grubler, A. *et al.* A low energy demand scenario for meeting the 1.5 degrees C target and sustainable development goals without negative emission technologies. *Nature Energy* **3**, 515-527 (2018).

58   EEA. Transforming Europe's food system: Assessing the EU food system policy mix. (European Environment Agency (EEA), Luxembourg, 2023).

59   EEA. Sustainability transitions:policy and practice. (European Environment Agency, Copenhagen, Denmark, 2019).

60   Wallace-Stephens, F., Morgante, E. & Mrvcic, V. Rural and post-industrial perspectives on the just transition. (Scotland, 2023).

61   ILO. Employment and just transition to sustainability in the BRICS countries. (International Labour Office, 2022).

62   TNRTP. Tamil Nadu Rural Transformation (Vazhndhu Kattuvom) Project. (Department of Rural Development & Panchayat Raj, Government of Tamil Nadu, 2018).

63   Nilsson, A. E. *et al.* Towards extended shared socioeconomic pathways: A combined participatory bottom-up and top-down methodology with results from the Barents region. *Global Environ. Change* **45**, 124-132 (2017).

64   Newell, P. J., Geels, F. W. & Sovacool, B. K. Navigating tensions between rapid and just low-carbon transitions. *Environmental Research Letters* (2022).

65   Whitfield, S. *et al.* A framework for examining justice in food system transformations research. *Nat. Food.* **2**, 383-385 (2021).

66   Chambers, J. M. *et al.* Six modes of co-production for sustainability. *Nat. Sustain.* **4**, 983-996 (2021).

67   IFAD. Khyber Pakhtunkhwa Rural Economic Transformation Project. (International Fund for Agricultural Development, 2021).

68   Kemp, R. Technology and the transition to environmental sustainability. *Futures* **26**, 1023–1046 (1994).

69   Markard, J., Raven, R. & Truffer, B. Sustainability transitions: An emerging field of research and its prospects. *Res. Pol.* **41**, 955-967 (2012).

70   Geels, F. W. & Schot, J. Typology of sociotechnical transition pathways. *Res. Pol.* **36**, 399-417 (2007).

71   Folke, C. *et al.* Resilience thinking: integrating resilience, adaptability and transformability. *Ecol. Soc.* **15**, 20 (2010).

72   Haasnoot, M., Lawrence, J. & Magnan Alexandre, K. Pathways to coastal retreat. *Science* **372**, 1287-1290 (2021).

73   Leach, M., Stirling, A. C. & Scoones, I. *Dynamic sustainabilities: technology, environment, social justice*. (Routledge, 2010).

74   De Haan, F. in *Modelling Transitions: Virtues, Vices, Visions of the Future* Vol. 7 (eds E. A. Moallemi & F. De Haan) (Routledge, 2020).

75   Köhler, J. *et al.* An agenda for sustainability transitions research: State of the art and future directions. *Environmental Innovation and Societal Transitions* **31**, 1-32 (2019).

76   Moallemi, E. A. *et al.* Eight Archetypes of Sustainable Development Goal (SDG) Synergies and Trade-Offs. *Earth's Future* **10**, e2022EF002873 (2022).

77   Oliver, T. H. *et al.* Overcoming undesirable resilience in the global food system. *Global Sustainability* **1** (2018).

78   Dolfsma, W. & Leydesdorff, L. Lock-in and break-out from technological trajectories: Modeling and policy implications. *Technol. Forecast. Soc. Change* **76**, 932-941 (2009).

79   Turnheim, B. *et al.* Evaluating sustainability transitions pathways: Bridging analytical approaches to address governance challenges. *Global Environ. Change* **35**, 239-253 (2015).

80   van Beek, L., Hajer, M., Pelzer, P., van Vuuren, D. & Cassen, C. Anticipating futures through models: the rise of Integrated Assessment Modelling in the climate science-policy interface since 1970. *Global Environ. Change* **65**, 102191 (2020).

81   Reed, P. M. *et al. Addressing Uncertainty in Multisector Dynamics Research*. (Zenedo, 2022).

82   Srikrishnan, V. *et al.* Uncertainty Analysis in Multi-Sector Systems: Considerations for Risk Analysis, Projection, and Planning for Complex Systems. *Earth's Future* **10**, e2021EF002644 (2022).

83   Törnberg, A. Combining transition studies and social movement theory: towards a new research agenda. *Theory and Society* **47**, 381-408 (2018).

84   Moallemi, E. A. *et al.* Achieving the Sustainable Development Goals requires transdisciplinary innovation at the local scale. *One Earth* **3**, 300-313 (2020).

85   Voß, J.-P. & Bornemann, B. The politics of reflexive governance: challenges for designing adaptive management and transition management. *Ecol. Soc.* **16**, 9 (2011).

86   Brutschin, E. *et al.* A multidimensional feasibility evaluation of low-carbon scenarios. *Environmental Research Letters* **16**, 064069 (2021).

87   Grant, M. J. & Booth, A. A typology of reviews: an analysis of 14 review types and associated methodologies. *Health Information & Libraries Journal* **26**, 91-108 (2009).

88   Moallemi, E. A. *et al.* Knowledge co-production for decision-making in human-natural systems under uncertainty. *Global Environ. Change* **82**, 102727 (2023).

89   Hopia, H., Latvala, E. & Liimatainen, L. Reviewing the methodology of an integrative review. *Scand. J. Caring Sci.* **30**, 662-669 (2016).

90   Suurs, R. A. *Motors of Sustainable Innovation: Towards a Theory on the Dynamics of Technological Innovation Systems* PhD thesis, Utrecht University, (2009).