



Agency and behavior change in agricultural research for development: New directions for guiding agri-food system transformations

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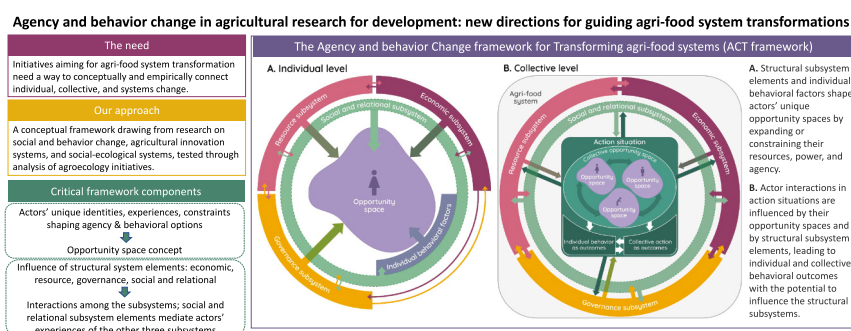
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HIGHLIGHTS

- Initiatives need to conceptually connect diverse actors' agency and behavior change dynamics with desired system changes.
- The ACT framework unpacks interactions among structural features and actor agency and behavior in food system transformation.
- ACT supports broader engagement with diverse agri-food system actors in research and initiatives.
- ACT enables a more deliberate assessment and communication of factors enabling or impeding behavior change.

GRAPHICAL ABSTRACT



Abbreviations: ACT, Agency and behavior Change framework for Transforming agri-food systems; AEI, CGIAR Initiative on Transformational Agroecology across Food, Land and Water Systems; AIES, Agricultural Innovation Ecosystem; AIS, Agricultural Innovation Systems; GBV, Gender-based violence; MLP, Multi-level Perspective; NGO, Non-governmental organization; SBC, Social and Behavioral Change; SES, Social-Ecological Systems; TOC, Theory of Change.

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ABSTRACT

CONTEXT: Agri-food system transformations require change across sectors and actors within the system. Initiatives contributing to these changes need to connect system change processes to individual and collective agency and behaviors.

OBJECTIVE: We propose a conceptual framework on agency and behavior change for transforming agri-food systems (ACT framework). ACT emphasizes agri-food system actors' behaviors with attention to their power, agency, and the influence of structural agri-food system elements. Researchers can apply ACT to assess an initiative's contributions to changes in system elements through individual and collective behaviors.

METHODS: We conducted literature reviews and key informant interviews for 29 initiative case studies. Using ACT, we identified patterns in terms of initiatives' targeted actors, behaviors, and the factors shaping actors' agency and behavior. We then applied ACT in an initiative in Zimbabwe to develop a theory of change that links behavior change pathways with broader systems transformation.

RESULTS AND CONCLUSIONS: The reviewed initiatives focused heavily on shaping producers' behavior through knowledge transfer, less often considering other actors and structural challenges and opportunities. Key informants frequently reported enablers and impediments to achieve initiative outcomes that were associated with structural system elements. Few were able to articulate their initiative's theory of change and underlying assumptions.

SIGNIFICANCE: ACT can support a more diverse and theory-based exploration of agri-food system initiatives' target actors, behaviors, and factors shaping behaviors. Development professionals can apply the ACT framework to design more effective TOCs that attend to diverse actor groups and leverage the factors influencing these actors' agency and behaviors.

1. Introduction

Increasingly, efforts to make agri-food systems more sustainable, equitable, and supportive of human wellbeing call for systems transformation (Klerkx and Begemann, 2020; Leeuwis et al., 2021; Woltering et al., 2019). Actors' behavior and agency across agri-food systems determine how systems transform: at the farm and farmer scale, within communities of producers and consumers, along value chains, within supporting systems of researchers and extension agents, and among policy makers and donors (Béné, 2022; Williams et al., 2023). As such, development actors need to conceptually link their understanding of system transformation—which is often focused on higher-level processes—with the more granular dynamics of individual and collective agency and behavior change among diverse system actors.

Behavior in agri-food systems includes activities of individuals or organizations, including agricultural practices, interactions between individuals or organizations, or business operations. We take as a fundamental premise that behaviors result from an intersection of internal factors and wider, external structures and conditions that enable behavior change and innovation (Leeuwis et al., 2021; Woltering et al., 2019; McGuire et al., 2024). This premise aligns with the idea that individual and structural change are interdependent processes (Kabeer, 1999). Kabeer (1999) defines agency most simply as the ability to choose one's goals and act upon them, further noting that agency is tied to the structure in which individuals operate, including their resource access and opportunities. Both agency and structure have “catalytic potential” to serve as entry-points to stimulate or drive change (Kabeer, 1999). Understanding agency-structure dynamics can help illuminate how change happens. For instance, how an idea on the margins can become highly influential (Gillard et al., 2016) and, more generally, how the interplay of agency-structure contributes to, or prevents, change and transformation processes. We further recognize the importance of actors having a choice. Actors should be able to deliberately participate in change processes to devise and sustain changes that result in outcomes beneficial to them (Moser, 2016).

From this perspective, initiatives that aim to support agri-food system transformation need to develop theories of change (TOCs) that are grounded in behavioral theories and perceptions of both the agency and structure of the agri-food system. Agricultural research for development often lacks holistic research and interventions, which can bridge the gap between individual-, niche-, or pilot-level and broader system change (Woltering et al., 2019; Leeuwis et al., 2021). There is a need for

research that bridges individual- and system-level understanding of change, including the factors that shape agency and behaviors of diverse system actors and the role they play in agri-food systems transformation processes, described as actor interactions with their context in Engler et al. (2019).

We propose a conceptual framework to bridge the gap between systems-level change and behavior change processes in approaches to agri-food systems transformation. This framework acknowledges factors shaping individual and collective behavior, actor interactions, and eventually system-level changes. The framework captures the unique opportunities available to different actors and their unequal power and agency affecting their opportunities, decisions, and behaviors within agri-food systems. The framework can support researchers in agricultural research for development to systematically assess factors shaping behavior and agency in agri-food system transformations. It can help to identify individual, collective, and systems change processes and gaps in the development approach. The framework can further support development actors (researchers included) in a reflective process to develop robust, effective, and inclusive theories of change built on knowledge and hypotheses on the range of factors shaping behaviors and transformation rather than on implicit beliefs (Maru et al., 2018; Douthwaite and Hoffecker, 2017; Conti et al., 2024a). Such TOCs would 1) attend to the roles of diverse system actors in bringing about change, and 2) systematically identify, prioritize, and leverage diverse factors that influence actors' agency and behaviors, thereby enabling progress toward the envisioned agri-food system transformation.

The paper proposes its framework in the following ways: (i) it explains the focus of existing conceptualisations of food systems transformation and draws upon other relevant theories to propose the ACT framework bridging individual behavioral and system change; (ii) it demonstrates the application of the ACT framework by unpacking the theory of change of an initiative in Tunisia, identifying which theory of change components align with ACT framework elements and the breadth of elements addressed; (iii) it applies the ACT framework diagnostically to assess the degree of attention to agency and behavioral changes in a range of agroecology initiatives; (iv) finally it applies the ACT framework in an iterative project design in Zimbabwe to demonstrate how it can strengthen project design and implementation practice to achieve desired results. The paper then discusses the importance of operationalizing the connection between system and behavioral change to support system change more effectively. It highlights the potential of the ACT framework to facilitate critical reflection of initiative's theories

of change.

2. Conceptualizing agency and behavior change in Agri-food system transformations

The impetus for developing a framework was to understand how initiatives that aim for system transformation engage with actors' agency and behavior change. A core team of four researchers within the CGIAR Agroecology Initiative (AEI) reviewed different frameworks and schools of thought on behavior and systems change to develop the framework. The framework was then shared and revised based on feedback of 16 other researchers in the AEI. The group of 20 researchers then used the framework to review entry points and outcomes of behavior change for agroecologically relevant initiatives in five countries. To generate further discussion, Voss et al. (2024) presented initial results of this analysis in a project report. This paper marks the next step in the development and application of the conceptual framework as it emphasizes its potential to structure a more diverse and theory-based exploration and development of effective, inclusive, and actor-centered TOCs for initiatives on agri-food system transformation.

To develop a framework that could bridge individual and systems level understandings of change, we started with two key frameworks that, if combined, could make this connection. These were the social-ecological systems (SES) framework (McGinnis and Ostrom, 2014) and the behavior change wheel (Michie et al., 2011). From there, we identified streams of literature that further revealed the elements of these frameworks and their connections. We focused on agri-food systems literature and investigated literature from other fields when necessary to fill gaps. From agri-food systems research, we included literature on systems transformation perspectives (e.g. Klerkx and Begemann, 2020; Leeuwis et al., 2021; Woltering et al., 2019; Conti et al., 2021), diverse actors and their interactions (e.g. Shang et al., 2021; Williams et al., 2023), a TOC approach to intervention strategies (e.g. Thornton et al., 2017; Maru et al., 2018), social context, power and agency (e.g. Conti et al., 2021; Sumberg and Okali, 2013), and the role of policies and governance (e.g. Shang et al., 2021; Conti et al., 2021). We found that individual behavioral factors, especially psycho-cognitive factors such as motivations and aspirations, were rarely present in agri-food systems literature (with some exceptions, such as Shang et al., 2021; Engler et al., 2019; Mausch et al., 2021). Our framework development process therefore drew on additional social and behavior change literature (e.g. Petit, 2019; Michie et al., 2011).

2.1. Systems perspectives on transformation

The SES framework emphasizes that the performance of a system strongly depends on how well governance mechanisms are aligned with the social-ecological system (McGinnis and Ostrom, 2014; Ostrom, 2009). Effective governance processes are embedded in history and context (Leach et al., 2007). Misaligned governance is one of the main obstacles to agri-food system change (Conti et al., 2021). Actors' interactions are shaped by the actors' characteristics, their access to resources and services, and by structural components of systems, including social, economic, governance, and ecological subsystems (Bak-Coleman et al., 2021). Actors' behavior and interactions create dynamic feedback to these structural subsystems (McGinnis and Ostrom, 2014) which creates entry points for imagining structural and transformational change.

Geels and Schot's (Geels, 2002; Geels and Schot, 2007) multi-level perspective (MLP) on sociotechnical transition acknowledges that innovations occur in the context of a macro-level sociotechnical landscape. Such landscapes consist of relatively static external factors such as the macroeconomic context, political developments, and culture, which "do not determine [actions], but provide deep-structural 'gradients of force' that make some actions easier than others" (Geels and Schot, 2007, p. 403). Anderson et al. (2019) applied the MLP framework to

agroecological transformation processes, exploring actor-level concepts of self-organization and power. They identified six "domains of transformation" through which agroecological innovations can break into dominant sociotechnical regime: access to natural ecosystems, knowledge and culture, systems of exchange (markets), networks, discourse, and equity.

2.2. Accounting for diverse actors and their interactions

The SES framework develops the concept of 'action situations'—structured social spaces where actors learn, take decisions, and interact to achieve outcomes (Ostrom, 2011). Research on agricultural innovation systems (AIS) similarly offers powerful entry points for conceptualizing an actor-centered system transformation perspective. AIS focuses on developing and disseminating innovations that are essential for transforming systems. Innovations are viewed as social processes involving a wide range of stakeholders. They include technological developments and changes in social, economic, and institutional conditions (Klerkx et al., 2012; Klerkx and Begemann, 2020; Rajalahti et al., 2008). Such conditions shape behavioral incentives for actors. AIS frameworks emphasize the role of formal institutions conducting research, extension, education, and training. These organizations are critical to disseminating innovations. Several conceptual frameworks emerged from AIS. Agricultural innovation ecosystem (AIES) approaches acknowledge power dynamics and interactions (Pigford et al., 2018). Mission-oriented innovation systems (MIS) are another extension of this school of thought, emphasizing that transformational innovation processes are driven by collective agendas (Klerkx and Begemann, 2020; Pigford et al., 2018).

2.3. Social context, power, and agency

Powerful actors and power imbalances shape the direction of system change (Conti et al., 2021). Power imbalances occur on different levels in the system such as within value chains, sectors, communities, and households. The SES literature recognizes the role of individuals as change agents or "institutional entrepreneurs" in system transformation (e.g., Westley et al., 2013; Charli-Joseph et al., 2018). They recognize that actors are heterogeneous in their agency and that their opportunities shift based on their access to resources, position in social networks, access to power, and even actors' own awareness of their agency. The AIS literature acknowledges the importance of power in multi-actor innovation processes (e.g., Pigford et al., 2018; Eidt et al., 2020; Kok and Klerkx, 2023).

Power and agency have been the subject of a particular subset of literature on gender and agricultural innovation (Badstue et al., 2020; Farnworth et al., 2018; Petesch et al., 2018) and sustainable agri-food systems transformation (Avelino and Wittmayer, 2016; Pigford et al., 2018). Power and agency arise largely from social context, which therefore emerges as an important concept for understanding agri-food system actors' behavior. Social norms, for instance, provide a psychological framework that people use to navigate their social environment (González, 2024). Social norms describe the behavior that people think is approved by others or commonly observed (Cialdini et al., 1991). What behavior is approved for whom strongly depends on actors' identities. In most societies, the strongest identities are socially assigned from birth, like gender and ethnicity (Kabeer, 2014). Intersectional identities emerge in interaction with other characteristics such as age, education level, religion, literacy, marital status, disability, or language. Intersectional identities create heterogeneous experiences and constraints for actors. Identity-related social advantages or marginalization influence actors' opportunities (Crenshaw, 2017; Rietveld et al., 2023). Research on social differentiation in agricultural systems has introduced the concept of 'opportunity space' to describe the livelihood pathways available to different groups in society (Bullock and Crane, 2021; Rietveld et al., 2020; Sumberg and Okali, 2013).

Context-specific social norms and identities shape actors' relations and network structures within systems. Despite their persistent nature, norms and identities can change (Badstue et al., 2020; Kantor et al., 2015) which alters the dynamics of individual decisions and actor interactions. Social norms and identities are interconnected with paradigms, which have been described as the most powerful levers to change systems (Meadows, 2008; Harper et al., 2020).

2.4. Cognitive-psychological factors influencing behaviors

As much as system transformation requires collective action, understanding individual behaviors is at its foundation (Engler et al., 2019). The extensive psychological literature around social and behavior change (SBC) provides powerful theories for conceptualizing system actors' behavior (reviewed in Petit, 2019). These theories describe behavior as the result of the interaction of internal processes and characteristics, including individuals' knowledge and skills, aspirations and motivations, and so-called cognitive biases. Cognitive biases are systematic thought processes which depart from standards of logic and accuracy and simplify situations (Haselton et al., 2015). Time and risk preferences are examples of cognitive biases that can cause behavioral outcomes to diverge from so-called core motivations. Actors might, for instance, prefer immediate benefits over substantially higher future benefits (Hausman, 1979; O'Donoghue and Rabin, 2015). Actors' motivations are another cognitive-psychological factor. Motivation refers to processes that initiate and energize goal-oriented behavior (Michie et al., 2011; Max-Neef et al., 1991). Behavior is motivated by the desire to fulfill needs such as for subsistence, safety, affection, esteem, self-actualization (Maslow, 1987), understanding, participation, recreation, creation, identity, freedom (Max-Neef et al., 1991), competence, and autonomy (Ryan and Deci, 2020).

2.5. Key concepts for conceptualizing behavior change in Agri-food systems

Based on our review, we identified seven key concepts that help to bridge behavior change and system transformation, acknowledging: 1) diverse system actors; 2) their individual behaviors; 3) their interactions, including collective action; 4) the role of individual behavioral drivers; 5) structural subsystems; 6) social and relational dynamics; and 7) actors' agency and power dynamics.

3. A comprehensive framework for agency and behavior change in Agri-food systems

The agency and behavior change framework for transforming agri-food systems (ACT framework) conceptualizes how individual actors' opportunity spaces are created (Fig. 1 A) and how the system context and actors' opportunity spaces influence actor interactions, influence individual and collective behaviors, and create feedback to the context, potentially leading to structural changes (Fig. 1B). ACT thus bridges individual, collective, and systems change. To organize the key concepts identified in the review of frameworks and schools of thought, we: 1) highlighted how actors' opportunities are shaped by individual factors, as shown in the gray box on the lower right edge of the opportunity space in Fig. 1 A; 2) placed the action situation at the center of the collective framework, as shown in the green box in Fig. 1B; 3) emphasized structural subsystems of the agri-food system, including economic, governance, social and relational, and resource subsystems; and 4) acknowledged the differing experiences of individual actors, groups, or organizations, especially in relation to their intersectional identities, and their constraints, needs, and opportunities (represented by the three different opportunity spaces in the center of the action situation in Fig. 1B).

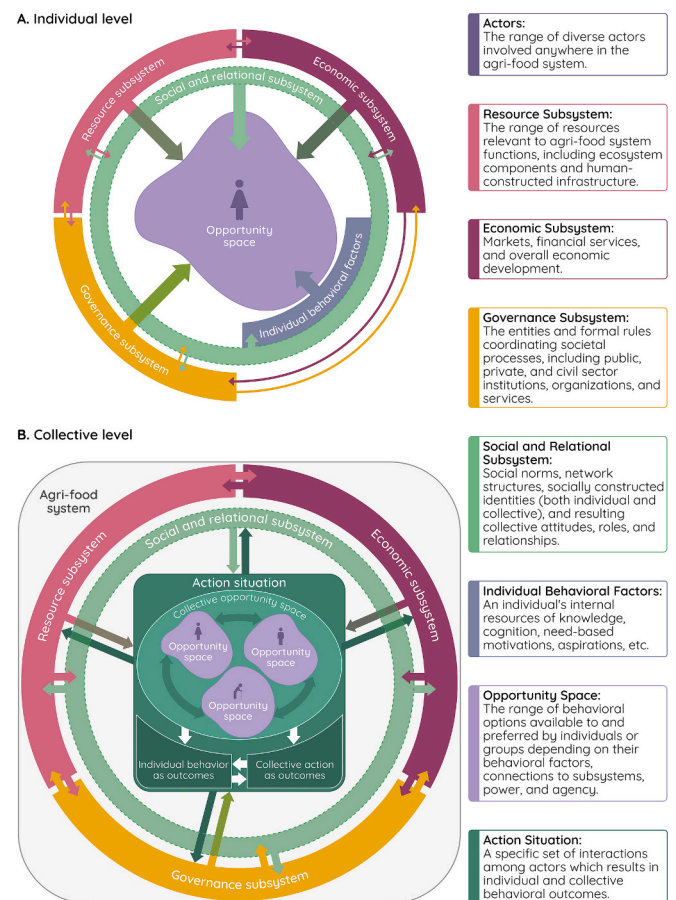


Fig. 1. A conceptual framework on agency and behavior change for transforming agri-food systems (ACT). A. Structural subsystem elements and individual behavioral factors shape actors' unique opportunity spaces by expanding or constraining their resource access, power, and agency. Interactions occur among the different elements as they influence the opportunity space. B. Within an agri-food system, actors' interactions in action situations are influenced by their opportunity spaces and by structural subsystem elements, leading to individual and collective behavioral outcomes.

3.1. Actors

The ACT framework considers a broad range of actors, understood as individuals, groups, or organizations across sectors. For instance, in agri-food systems, producers, other value chain actors, extension agents, consumers, researchers, policymakers, civil society organizations, and academics play a role. Which actors need to be considered when applying ACT depends on the case's specific context.

3.2. Individual behavioral factors

An actor's knowledge, need- and aspiration-based motivations, and cognitive characteristics strongly influence their opportunities, behavior, and interactions. Individual behavioral factors vary across actors and may change over time.

3.3. The governance subsystem

We understand governance as a multi-level subsystem coordinating, steering and creating accountability in complex networks of actors operating across levels (Leach et al., 2007). Diverse rules, laws, contracts, and other institutions organize the processes within a system, most importantly actor interactions (Loft et al., 2015). These institutions affect the way people access knowledge, resources, and social

connections (de Roo et al., 2019) and create external motivations (Meinzen-Dick and Bruns, 2024).

3.4. The resource subsystem

The resource subsystem includes the range of natural resources such as soil, water, ecosystems, biodiversity, and climatic conditions, which form the basis for agricultural production. Human-constructed infrastructure, such as roads, dams, canals, storage facilities, and information technology, are also included. The resource subsystem therefore entails all biophysical and technological processes that contribute to creating goods and services (Hinkel et al., 2015).

3.5. The economic subsystem

The economic subsystem constitutes overall economic development, including the market conditions actors encounter for inputs, outputs, and financial services. It also includes the institutions organizing the exchange of goods and services. The economic subsystem can create strong external motivations for system actors, which can support or hinder system transformation.

3.6. The social and relational subsystem

Our framework highlights the critical role of the social and relational subsystem. We define it as collective attitudes, roles, relationships, network structures and social norms, and the dynamics associated with control over resources that result from these. Elevating social and relational dynamics as a separate subsystem makes their role in shaping behavioral outcomes more visible while acknowledging their potential as an entry point for influencing actor behavior.

The social and relational system permeates multiple aspects of the agri-food system, including individual behavior and the structural subsystems. They shape individuals' motivations, knowledge, and biases. Actors' ability to make and act upon decisions, both individually and collectively, is therefore tied to their unique intersectional identities and the power and agency afforded to them within their social and relational subsystem context. The social and relational system further mediates actors' involvement with governance, economic, and resource subsystems. This is represented in Fig. 1 by placing these subsystems outside the social and relational subsystem. Their influence on opportunity space is represented by arrows passing through the social and relational subsystem.

3.7. Opportunity spaces

We understand opportunity spaces as the range of behavioral options available to and preferred by individuals, groups, or organizations (Rietveld et al., 2020; Sumberg and Okali, 2013). Opportunity spaces reflect actors' power, agency, and access to resources and assets. An actor's individual behavioral factors intersect with their experience of structural factors, mediated by their intersectional identity, to influence the actor's opportunity space and set the conditions for agency and behavior change. Intersectionality refers to actors' multi-dimensional identities and how these uniquely shape their experiences (Crenshaw, 2017). For example, poor women in a marginalized social class might encounter different constraints and opportunities than wealthier women. Thus, the social and relational subsystem determines access to and control over resources, markets, institutional services, infrastructure, decision-making spaces, or employment (Avelino and Wittmayer, 2016; Kabeer, 2014; Djoudi et al., 2016).

3.8. Action situations

Action situations are social spaces in which actors learn, make decisions, and interact to achieve outcomes (Ostrom, 2011). In the ACT

framework, the action situation is where individual and collective behaviors are enacted. Action situations are structured by institutions originating from the governance, economic, and social and relational subsystems. Actors' interactions are further influenced by each actor's opportunity space.

3.9. Collective action and collective opportunity spaces

Collective action emerges as the result of individual actors' goal- or mission-oriented interactions (Ostrom, 1990; Klerkx and Begemann, 2020). Within the action situation, synergies between actors' individual opportunity spaces create collective opportunity spaces that determine the range of possible collective behavioral options in the agri-food system. This can foster collective action or create conflict. For example, when power dynamics determine which paths are taken, some actors may find themselves excluded or have less opportunities.

3.10. Feedback from the action situation to the structural subsystems

Individual behavior and collective action as outcomes of the situation may influence the governance, economic and social and relational subsystems (McGinnis and Ostrom, 2014). They are an important dynamic element of the ACT framework. Through feedback, structural elements of the agri-food system can be influenced. Depending on what kind of interactions happen in the action situation, they can create transformational system change.

4. Materials and methods

We compiled an inventory of initiatives in five countries with diverse experiences in agroecological transitions and where AEI teams were present, namely India, Kenya, Peru, Tunisia, and Zimbabwe. The inventory was based on existing project databases, expert consultations, and a review of information available on the internet. We then drew from the inventory to select five to eight initiatives from each country, totaling 29 initiatives (Supplementary Table A), based on the following selection criteria:

- Engagement with multiple and diverse agroecological practices and principles to represent a diversity of intended outcomes (i.e., focusing not only on resource-conserving agronomic practices but also on social and economic outcomes).
- Scale of reach that provided broad geographic representation within the agri-food system of focus (i.e., regional or landscape-scale initiatives, especially in the target regions of AEI, were prioritized over very localized initiatives). Temporal scale was not a consideration.
- Diversity of the type of initiative to represent a diversity of designs and planning processes (project, government program, social movement, community initiative).
- Relevance to the local agroecological transition as reported by local stakeholders, primarily with attention to initiative impact.

Subsequently, with the support of local research teams, we conducted key informant interviews with one or more individuals involved in designing and implementing each selected initiative. Key informants were representatives of implementing organizations or government agencies, project field agents, or participating farmers or other food producers. We developed a standardized semi-structured interview protocol to collect information about seven features of each initiative: 1) the TOC or the rationale for the behaviors addressed, 2) the targeted actors, 3) targeted behavior changes, 4) interventions, 5) assumptions behind interventions, 6) social inclusion efforts, and 7) perceived enablers or impediments to the intended changes. On this last feature, we were not aiming for reductive interpretations of what caused success or failure, but rather, similar to Conti et al. (2024a), we aimed to gain more insight into the perceived pathways of achieving intended changes that

emerged or became more apparent during initiative implementation. We compiled notes of the interviews or, when possible, we recorded the interview and then transcribed and translated it into English. We then reviewed available gray literature (often proposals and reports) to confirm information on the initiatives' features, although the available gray literature did not cover all initiatives and features.

We coded the interviews and gray literature to develop typologies of targeted actors, behaviors, interventions, social inclusion efforts, and perceived factors enabling and impeding behavior change (Supplementary Table B4). While most of the typologies emerged from the coding process, we built on established typologies for interventions employed for behavior change (Abraham and Michie, 2008; Kok et al., 2016) and social inclusion efforts (UNFPA, UNICEF, and UN Women, 2020). We further coded each of the targeted behaviors and interventions with the ACT framework element that was intended to be influenced (individual behavioral factors, action situation dynamics, or the economic, resource, governance, or social and relational subsystems). We quantified patterns and trends of five of the investigated features (2,3,4,6, and 7) across the 29 case studies. We then identified emblematic cases that illustrated the emerging quantitative and qualitative findings in more detail. This approach allowed us to respond to our research questions and to test the ACT framework's utility in supporting initiative design: 1) attend to the roles and opportunities of diverse system actors in bringing about change and 2) systematically identify, prioritize, and leverage diverse factors that influence actors' agency and behaviors. We illustrate this first through an in-depth look at an initiative from Tunisia. Next, we identify patterns across the 29 initiatives in terms of targeted actors and behaviors, strategies for behavior change, informants' awareness of the initiative's ToC and underlying assumptions, and informants' perceptions of the key factors enabling or impeding the intended changes.

Finally, we formulated an approach to apply the ACT framework and an associated line of questioning to develop more comprehensive TOCs that link behavior change pathways with broader systems transformation. As part of elaborating and refining such a TOC, the AEI's Zimbabwe team followed a participatory research approach in Mbire and Murehwa districts. The team conducted farmer-led visioning exercises and stakeholder mapping. They identified agricultural transition milestones and the implications for actors' agency and behaviors. A total of 472 stakeholders—across community, governance, private sector, and development spheres—were engaged through key informant interviews, focus group discussions, and iterative action planning. Drawing from the experience of the Zimbabwe team in developing and refining a TOC, we illustrate how a pathway for a specific desired change can be elaborated by applying the ACT framework.

5. Results

5.1. Unpacking agency, opportunity space, and behavior change targets of an initiative using the ACT framework

For an initiative in Tunisia, we first identified the desired outcomes: sustainable soil and water management; conservation of existing natural resources; diversified production; integrated crop-livestock systems informed by conservation agriculture; and capable local actors. We then identified the actors and behaviors the initiative targeted and which of the ACT framework elements, as factors shaping actors' agency, opportunities, and behaviors, were addressed by the initiative's interventions (Supplementary Table C). We provide in bold below the framework element addressed by the interventions.

The initiative engaged a range of actors; farmers were engaged as individuals and as groups, primarily through existing (women's) farmer cooperatives. Extension agents, credit providers, and seed suppliers were also engaged, primarily to improve the connection and interaction between farmers and these actors. Networks of government organizations, researchers, and technical advisers were engaged to better address

natural resource management, fodder and animal health. A range of factors shaping these actors' agency/opportunities and behaviors were identified and addressed, touching on all six elements in the ACT framework and thus illuminating multiple pathways to achieve changes in behavior through targeted interventions.

One such pathway for intervention was based on the understanding that farmers required knowledge to effectively implement water and soil management practices. For this pathway, the interventions engaged both farmers and extension agents to improve their knowledge acquisition and dissemination behaviors (individual behavioral factors) through demonstrations, on-farm monitoring, and raising awareness. The initiative planners acknowledged that many women farmers experienced limited access to knowledge-sharing resources. To address this problem, the initiative provided women farmers with mobile phones. Initiative implementers then used text messages to share knowledge among farmers (resource subsystem).

Another intervention—a "knowledge hub" that facilitated more interaction, bringing together the relevant actors in a new way and integrating research and extension for natural resources, fodder and animal health—was based on two premises. First, independent and disconnected actions of research, government and extension actors hinder knowledge sharing and innovation in livestock and natural resource management. Second, government actors have sufficient influence to bring stakeholders together under a unified vision. These two premises guided the initiative planners to develop the collective and interactive approach of the knowledge hub that addressed the interactions (the action situation)—or lack thereof—that were shaping the actors' agency and opportunities.

Activities prior to this initiative's development focused more narrowly on testing technologies with the support of selected lead farmers. Initiative designers noted the limited scope and achievements through these activities and the potential for a wider scope by involving a range of actors and a systems perspective as they designed the initiative. This insight led them to the broad outcomes envisioned for the initiative and the consideration of diverse elements in the intervention premises. To achieve the initiative's broad outcome, the project designers realized that working with farmer cooperatives would make it easier to intervene through more diverse approaches. They understood that a "system of local actors" as well as a "nested" organization of government, research, and extension actors (action situation) were necessary to achieve and sustain the desired change and could be achieved through the knowledge hub approach.

The systems perspective enabled key stakeholders to recognize the diverse factors shaping farmer and other actors' opportunity spaces, including factors beyond the ones addressed by the initiative's intervention. One key informant noted that perhaps not enough was done to address policies that influenced or constrained actors' opportunities. Another noted that crop failure during some interventions indicated a need to better ensure the suitability of promoted crops to the variable climate. These key informants also recognized that a more thorough investigation of the unique needs of individual actors and a more organized approach to monitoring and reflection on the progress of the interventions could enhance the success of future initiatives. Additionally, key informants identified the need to identify and test legal solutions to allow the direct transfer of funds to communities and professional associations (governance subsystem).

In the end, many of the initiative's interventions enabled behavior change. Key informants specifically highlighted how the initiative had facilitated collaboration and trust-building between system actors. For example, stakeholders worked together through the knowledge hubs. Through a co-design process, seed suppliers and researchers developed a forage seed mixture that farmers provided specifications on, trialed, and demonstrated. The seed company then marketed these mixtures at a larger scale. Key informants reported that knowledge and promoted practices had spread beyond the immediate intervention area, in part thanks to the knowledge hubs with the participation and ownership of

relevant government agencies and the self-sustained extension services led by farmers and local extensionists.

5.2. Case study patterns in attending to the roles of diverse actors in bringing about change and the strategies to leverage actors' opportunities

Using the ACT framework as a lens, we assessed patterns among the twenty-nine initiatives examined in depth to identify common trends in how initiatives engaged with actors and their behaviors.

5.2.1. Target actors and behavioral changes

From the reported approaches of the 29 initiatives, we inductively identified seven types of target actors for behavior change (Fig. 2A): producers, including farmers, fishers, pastoralists, and other food producers as individuals (1); producer groups (2); other value chain actors, including retailers, input sellers, and actors in post-harvest activities (3); extension and education actors, including national agricultural extension agents and researchers (4); communities, including groups of natural resource users (5); governance actors, including policy makers and donors (6); and food consumers (7). All the initiatives targeted individual producer behaviors (1). Most initiatives targeted at least one

additional actor group, often with the intention to indirectly influence producer behavior. Initiatives mainly aimed to change on-farm activities, such as changing or diversifying the farm production portfolio, making up 45 % of cases. Initiatives also sought to engage producers in value chains by collaborating and negotiating with value chain actors (41 % of cases; Fig. 2B).

Initiatives' attention to diversity, equity and inclusion varied. Five initiatives (17 %) appeared to disregard social inclusion and equity concerns, with no discernible attention to differences in participation or outcomes for different groups of participants. The greatest share of initiatives (38 %) made some effort to include actors from marginalized groups, expanding their opportunity spaces. Generally, such activities consisted of tailoring training programs and outreach specifically to women, youth, people with disabilities, or tribal groups. Six initiatives (21 %) deliberately aimed to shift social and relational dynamics to improve the standing, agency, and opportunities of women and marginalized groups. For instance, some initiatives elevated women leaders or trained households and communities around gender equity.

Attention to social inclusion and equity did not guarantee equitable outcomes, however. Even in initiatives aimed explicitly at transforming social and relational dynamics, challenges arose. For example, a Kenyan

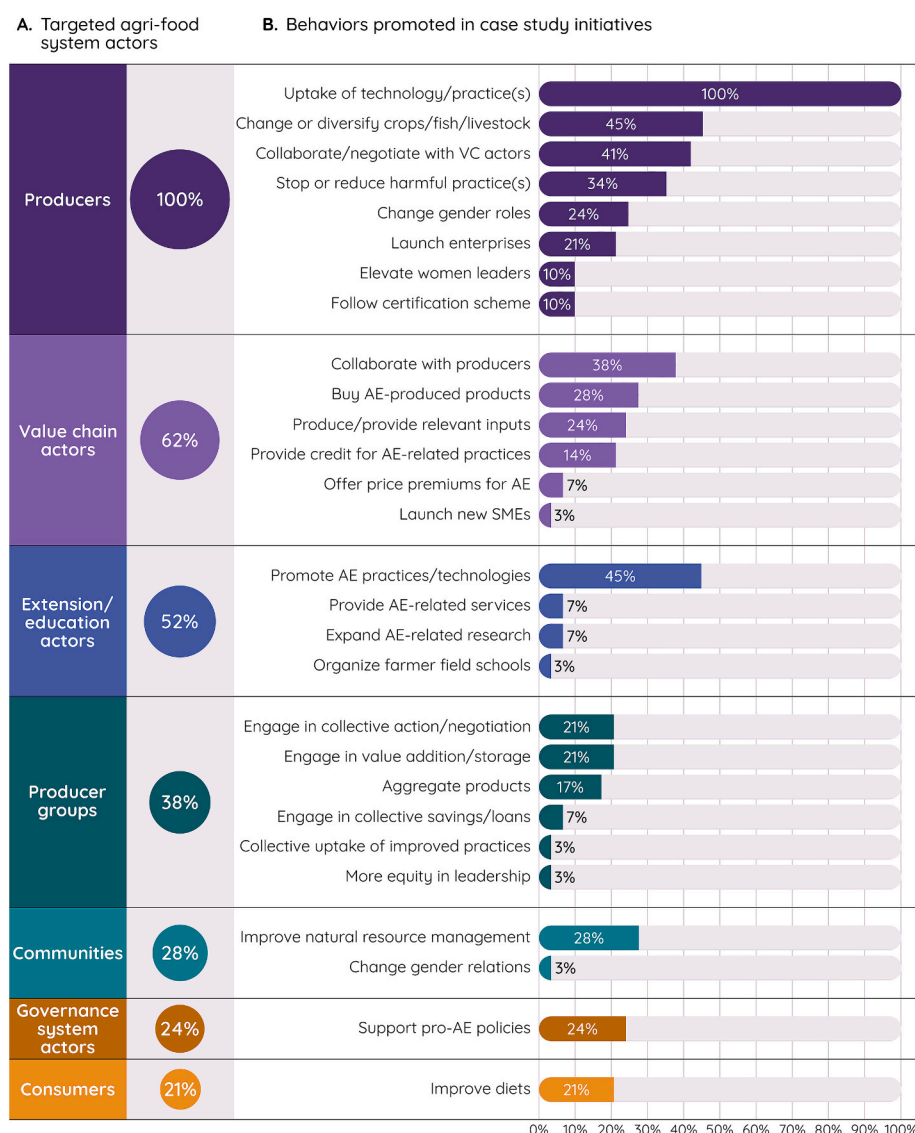


Fig. 2. A. Frequency at which agri-food system actors were targeted for behavior change by initiatives, and B. the associated behavior changes promoted for each actor group in the sample of case study initiatives. Percentages are based on the total reports from all case studies (29 total). Each initiative typically targeted multiple actor groups and behaviors.

initiative focusing on coffee applied gender equity training to household decision-making, particularly concerning income. They trained leaders of cooperatives and provided financial support to women and youth for establishing tree nurseries. Although a substantial gain in women's leadership was achieved with 40 of the 51 cooperatives integrating women into leadership positions, structural barriers to women's leadership remained largely unchanged, resulting in women's limited meaningful participation. One substantial barrier was the requirement for cooperative board members to supply at least 1000 kg of coffee, a quota that many women struggled to meet. This indicated a need for further work during the initiative to identify equitable outcomes and address key structural barriers.

5.2.2. Initiative strategies to trigger behavior change

We identified 17 types of interventions across the initiatives and linked these to the ACT framework elements (Fig. 3). Individual behavioral factors were by far the most common target of interventions to trigger behavioral change. All initiatives employed technical assistance, training, demonstrations, and/or modeling to shift behaviors, focusing on producer knowledge and awareness specifically. Two thirds of initiatives also leveraged strategies related to public advocacy (66 %) and one third to individual resource-building (31 %).

Among the initiatives that primarily focused on improving producer knowledge, change was expected to occur through informal diffusion of promoted practices through and beyond communities: "When the farmer listens or observes that, for example, the experimental plot with a lead farmer has given a good yield, curiosity and the desire to have a good yield at home automatically lead to a change in behavior" (key informant response). Key informants of some of these initiatives also reported substantial abandonment of practices after the initiative's end. They attributed this to the poor suitability of introduced practices and unsupportive legislation. Some key informants attributed the lack of change realized to intrinsic shortcomings of the target actors, labeling them as "resistant," "disinterested," or "laggards." Such perceptions reveal: 1) a frustration that implemented interventions did not lead to the intended outcomes; and 2) a lack of further reflection on whether the

interventions missed influential behavioral drivers that could have triggered behavioral change.

In addition to activities aimed at expanding producer knowledge, many initiatives (76 %) facilitated stakeholder interactions in the action situation by building or strengthening producer organizations or multi-stakeholder platforms. These interventions fostered social learning, resource sharing, and collective action and bargaining among producers, as well as expanded interactions between producers and other value chain actors. Overall, structural elements received less attention than individual behavioral factors. Engagements with governance subsystems were the least common. On average, initiatives targeted two of the four structural subsystems.

5.2.3. Initiative theories of change, assumptions, and factors enabling or impeding change

Although key informant interviews aimed to capture TOCs and assumptions behind initiatives' intervention strategies, informants were able to provide information on these for only 13 of the 29 initiatives examined. Informants often connected the interventions to overarching initiative objectives, but knew little about, and did not necessarily have access to, TOCs. They could offer few insights about the assumptions underlying the initiative TOC and activities. The assumptions underlying TOCs were generally not documented. Therefore, we inferred them from key informant descriptions of initiative objectives, interventions, and factors affecting behavior change. Key informants' perceptions of the factors enabling or impeding behavior change point to the relevance of diverse elements of the ACT framework (Fig. 4). Although the majority of factors reported to have enabled or impeded change were related to individual behavioral factors or actor interactions, structural enabling or impeding factors such as market chain opportunities (which we associated with the economic subsystem) and policies (associated with the governance subsystem) were frequently mentioned as enabling factors. Factors associated with the resource and social and relational subsystems were less frequently reported.

For some enabling and impeding factors, the likelihood of reporting correlate with an initiative's engagement with associated subsystems.

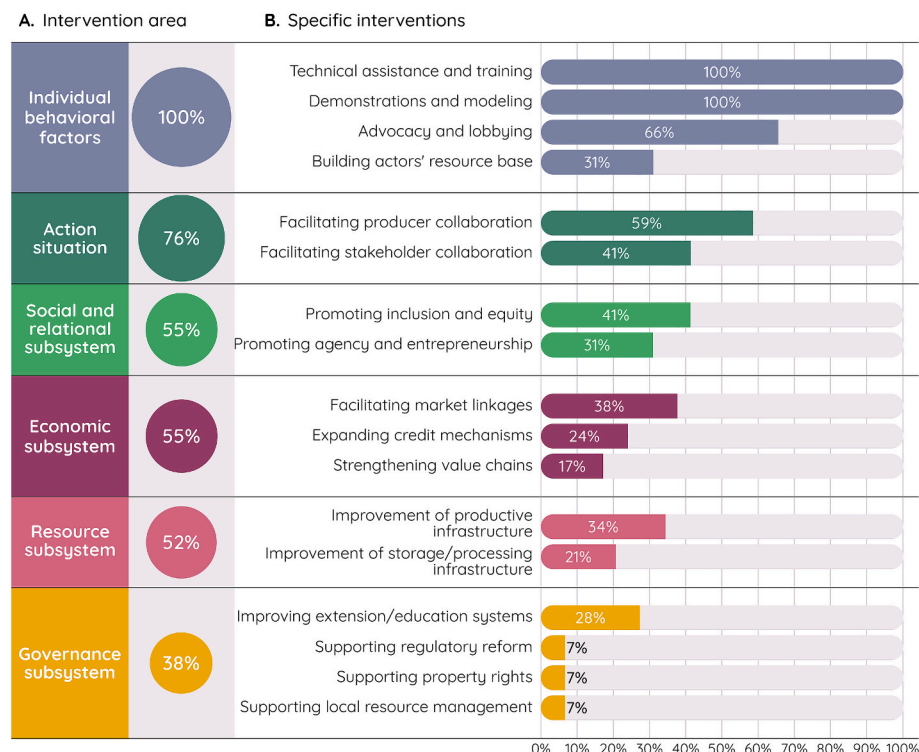


Fig. 3. A. Targeted Intervention areas of the conceptual framework. B. Specific intervention types employed to support behavior changes in case study initiatives.

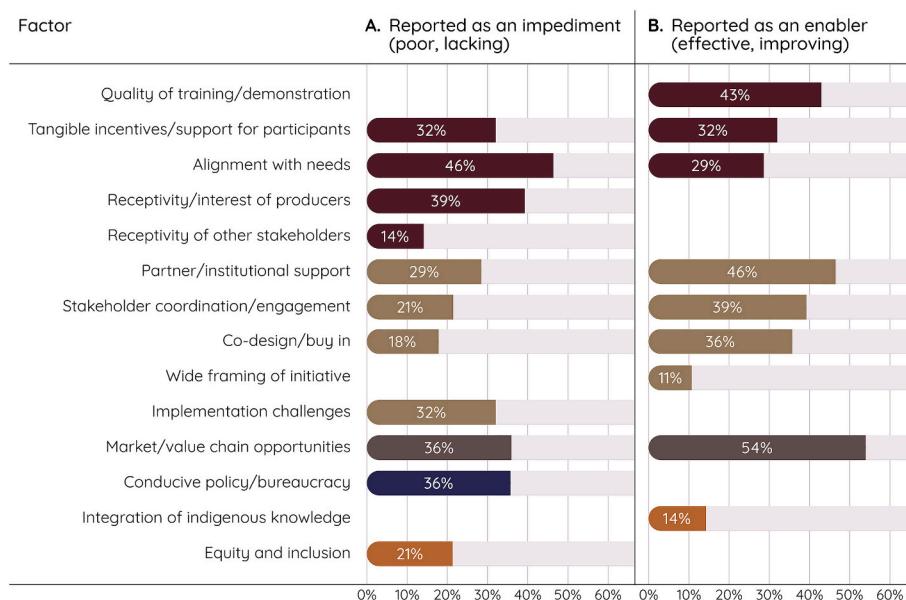


Fig. 4. Frequently reported factors (multiple responses permitted) perceived to A) impede or B) enable initiatives' intended behavior changes related to multiple elements of the ACT framework: individual behavioral factors appear in dark brown, the action situation in light brown, economic subsystem in gray-brown, governance subsystem in navy blue, and social and relational system in orange. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

For example, when comparing initiatives that addressed the economic subsystem versus those that did not, the key informants of the former more often reported market and value chain opportunities as an enabling and/or impeding factor (69 % compared to 46 %). Respondents for initiatives addressing governance subsystem elements, when compared to initiatives that did not, were more likely to report enabling factors related to partner or institutional support (73 % compared to 28 %), and wide stakeholder engagement (55 % compared to 28 %). They also more often reported impeding factors associated with policies or bureaucracy (64 % compared to 17 %).

Several enabling or impeding factors were associated with individual motivations, such as incentives, needs alignment, actors' interest and buy-in. These factors were more frequently reported as an impediment, indicating the need to better align initiatives with actors' motivations. Considering the initiatives' main intervention strategies, it is striking that availability or lack of knowledge was hardly perceived to be enabling or impeding factors. Initiative informants may have felt they have good control over transferring knowledge, supported by reported enabling factors, such as quality training and integration of indigenous knowledge.

5.3. Applying the framework to ensure more transformative results from initiatives

Using the ACT framework in the design and early stages of an initiative can guide the exploration of individual and systems-level factors shaping actors' opportunities and behaviors. The framework can help initiative designers evaluate the likely actor responses to a proposed intervention. Starting with desired system change(s) identified, the process of applying the ACT framework can help develop a TOC. The process helps initiative designers consider: the diverse actors and behaviors involved in the change; the assumed or known factors shaping each behavior; the intervention(s) that could address each factor and any research needed to inform the development of interventions; and the implementer best placed to carry out the intervention. Actors can be included in these steps through a co-design approach.

The AEI team in Zimbabwe carried out this process to develop and refine a TOC, informed by a clear understanding of different actors'

agency and opportunity spaces. Local system actors participated in an exercise to develop a shared vision and action plan. Through this exercise and iterative engagements, four key changes were identified as desired and necessary for local agroecological transition: "improved farming practices, technologies, and livestock breeds," "increased income and access to markets," "strengthened natural resource governance," and "peace in families." The team conducted research to refine understanding of the factors shaping behaviors relevant for each of these desired changes and incorporated these insights into the initiative TOC.

During the Zimbabwe exercise, "peace in families" was identified as a desired and necessary system change. The primary aim of this change was to reduce gender-based violence (GBV) in farming households (actors and behaviors). Through interviews, the team gathered local actors' perceptions of the factors shaping this behavior. Farmers cited financial stress, food insecurity, conflict over use of farming income, gender inequalities primarily in decision-making and access to resources, and social norms that condone GBV (factors). These factors spanned multiple ACT framework elements, including individual behavioral factors as well as economic, resource, social, and relational subsystems. The team then identified interventions used by experienced practitioners, such as officials in the Ministry of Women Affairs, traditional leaders, and NGOs (implementers). These organizations emphasized the importance of using multiple approaches to address the factors shaping GBV behaviors. The approaches include livelihood diversification, non-violent conflict management, shifting norms to increase respect for women's rights, and raising awareness on reporting channels for GBV (interventions). These interventions included individual or household-based approaches, as well as collective ones. They addressed individual, economic, and social and relational factors affecting behaviors.

Next, the team considered how to ensure addressing the factors across multiple framework elements while also working from the strengths and opportunities of their own team, as well as other potential interveners to bring in as partners. Based on the information gathered, the team identified the following potential approaches to incorporate in their TOC: working more closely with local NGOs that implement multiple approaches to address GBV, encouraging local actors and agricultural partners to promote the benefits of empowering both women and men, investigate the feasibility of developing new value chains to diversify incomes, reinforcing messages of women's empowerment and

peace in families, and encouraging participation in GBV-interventions. If implemented all together, these approaches could enhance actor interactions around this issue in the initiative's action situation and address factors in the individual, economic, social and relational subsystems. Thinking about how actors may respond to the change pathway, the team recognized that the interventions led by experienced practitioners were often embraced in local communities. At the same time, the team recognized the potential for increased GBV behaviors if women's economic empowerment achieved through the interventions was perceived to displace men. The team recognized the importance of norm-shifting and collective empowerment to avoid this negative response.

As demonstrated through this example, applying the ACT framework in a TOC process and documenting the information gathered and decisions made along the way can ensure a more thorough understanding of the enablers and barriers to change and the relevant interventions to address them. Probing questions (Supplementary Table D) can further clarify the logic of what behaviors, drivers, and actors to prioritize, and what interventions and/or research to pursue. The framework thereby refers to diverse theories, not all of which are relevant in every case. The analytical focus in a specific context needs to be theory driven (McGinnis and Ostrom, 2014), which responds to the call by Maru et al. (2018) for building TOCs based on theory and not implicit beliefs. The theory-based assumptions derived from this process should be revisited periodically during an initiative to check for coherence and whether adjustments to interventions or assumptions are needed. At the end of the initiative, the next steps can be identified through the same process.

6. Discussion

The ACT framework is based on the notion that agri-food system changes are driven by individual and collective behavioral changes, which are themselves an outcome of intersecting internal and external factors (Abercrombie et al., 2018). This perspective is important for understanding and acting upon theories of transformational system change. Acknowledging that structural system features are also shaped by people highlights the need to understand what drives these people's behavior. This calls for a paradigm shift in development practice and policy. ACT provides a framework that can support initiative planners, funders, and implementers to unpack and address the interactions between structural features and actor agency and behavior that influence systems-level change. They can combine the ACT framework elements with existing tools to develop TOCs that explain who needs to do what differently in the system to support the envisioned system change. Such systems' TOCs can then be questioned and revised. They can form the basis for developing initiative TOCs that describe how an initiative supports the system change by influencing critical actors' behavior. Distinguishing between and connecting system and initiative TOCs may unfold new transformative potentials. In contrast, most initiative managers included in our review were unable to articulate any TOC.

6.1. The roles of diverse system actors and factors shaping agency and behavior in change processes

Identifying and understanding relations between diverse actors and institutions are pivotal to initiating change at scale (Abercrombie et al., 2018). Pathways to system transformation must also bring about change across diverse system elements (Conti et al., 2024b). As demonstrated in the effect of actors' increased collaboration on improving knowledge sharing networks and seed availability in the Tunisia case, actors' interactions and behaviors could induce changes on subsystem elements.

In reviewing the 29 case studies, we often found an over-reliance on behavior change strategies targeting individual producers despite initiatives' claims to wider agroecological transformation goals. Actors who can influence structural challenges and opportunities were less frequently targeted. In addition, the dominant focus of initiative

designers and managers on building producer knowledge to trigger adoption of specific innovations differs from a more systemic change perspective, where *opportunities* for behavior change are created (Anderson et al., 2019; Klerkx and Begemann, 2020; Leeuwis et al., 2021; Woltering et al., 2019). Most initiatives tried to influence the behavioral factors that are convenient to influence without managers being able to articulate underlying behavioral assumptions. Even initiatives aiming to enhance reach and benefits for marginalized groups employed training as the main intervention to achieve change, despite reports that constraints related to social norms and unequal resource access were an impediment to change for many. These findings are aligned with evidence that in many innovation processes social norms rather than knowledge are the limiting factor (de Roo et al., 2019; Badstue et al., 2018).

The focus on individual producer behavior also overlooks other agri-food system actors whose interactions create individual and collective behavioral outcomes. Our findings on the diversity of factors perceived to enable or impede an initiative's intended changes, including factors involving structural subsystems and non-producer actors, is supported by findings of Williams et al. (2023) that producers' capacities for change may vary by the dominant agri-food system regime and the associated variations in political, market, and resource structures and actors. In the Tunisia case study, initiative designers recognized and acted upon this by developing interventions that engaged a range of actors and addressing all six framework elements. Similarly, the initiative team in the Zimbabwe case recognized the range of actors and structural subsystem elements influencing behaviors through the application of the ACT framework.

The opportunity space concept usefully anchored our understanding of how structural subsystem elements influence behavioral outcomes. Reflection on structural elements' roles in shaping behavioral outcomes can inspire the design of more powerful complementary innovations (Sartas et al., 2020) acting on multiple elements of the system (Pitcock et al., 2020). From this follows the need to also build actors' capacity to influence structural subsystems (Olsson et al., 2014).

Generally, initiatives that engaged with structural subsystems did so to expand actors' opportunity spaces—for instance, by broadening producers' market opportunities, empowerment programs, or promoting policies to support desired behavior changes. By highlighting the role of social and relational subsystems in mediating actors' individual and collective experiences and shaping their opportunity space, the ACT framework centers power, agency, and social dynamics more explicitly than other frameworks (Geels and Schot, 2007; McGinnis and Ostrom, 2014; Pigford et al., 2018; Williams et al., 2023).

6.2. Applying lessons learned to theory of change development for initiative design and implementation

Our findings underscore the need to clearly articulate an initiative's target actors, behaviors, and factors shaping their behavior and agency. The ACT framework can support structuring such an actor-centered approach to initiative design aiming for system change (Anderson et al., 2019). The ACT framework can empower initiative teams to design and implement interventions based on a more strategic priority setting of critical actors' behaviors and the factors that influence their behavior and agency. Coupled with a detailed rationalization of the links between an initiative's strategies and changes in these factors—which can be achieved in a thorough TOC—and application of a monitoring and reflection process to assess the validity of the rationale and adjust accordingly, the underlying backcasting logic could ensure that an initiative's strategy is fit-for-purpose to achieve the intended behavior and agri-food systems changes.

We found little awareness among key informants of initiative TOCs and assumptions underlying behavior change strategies. This may result, at least in part, from the selection of informants; most were implementers who had limited involvement in initiative design. However, this

finding raises the concern that implementers are tasked narrowly with achieving specific outputs for ‘technology transfer’ (e.g., through producer training), but are often unaware of the intended pathways for behavior change and wider systems transformation. A more reflexive approach to implementation would enable learning and adaptation to achieve intended changes based on new understandings. In addition, a reflection on the range of factors enabling or impeding targeted behavior change at an early stage of initiative design could enable more strategic pathways for intervention, as demonstrated in the correlation of respondents’ acknowledgement of structural enabling or impeding factors with the structural elements addressed by the initiative they represented. The fact that many key informants also named motivational factors as influential calls for a stronger assessment of target actors’ interests and demands. Several of the reported enabling or impeding factors could be monitored throughout an initiative’s life cycle to indicate the likelihood of achieving the desired changes. These include: the alignment of interventions with the target group’s needs; the degree of partner and institutional support; the effectiveness of engagement and coordination among stakeholders; and the effectiveness of co-design and other participatory processes. This aligns with [Kapgen and Roudart’s \(2020\)](#) call to ensure initiatives are held more accountable for their impact by including in the design and evaluation methodological principles such as who is designing, implementing, and controlling an initiative, and how the initiative is assessed, implemented and evaluated.

Together, these findings provide arguments for designing, structuring, and funding initiatives in a way that permits the development of and continuous reflection on TOCs grounded in social-science theories. Some of the assessed cases demonstrated such an approach in designing interventions. To incorporate insights based on the ACT framework, initiative designers, implementers, and donors will need to reflect on lessons from past change efforts and collaborate with a range of actors to ensure the initiative can 1) contribute to the long, multi-actor process of inducing change on system elements and 2) make the most of available time and resources. These changes are in alignment with calls for agricultural research actors and organizations to consider how their capacities and modes of operation must change to meet the aims of agri-food systems transformation (e.g., [Conti et al., 2024c](#)).

6.3. Further developing the ACT framework

The findings suggest several new areas for research. Future research could more deliberately compare outcomes of initiatives promoting specific behaviors with those aiming to expand actors’ opportunities. Further understanding is also needed on how opportunity spaces shape interactions in action situations, in particular actors’ voicing of their interests, engagement in governance systems, and capacity to induce or resist changes. By creating awareness of the diverse factors influencing opportunity spaces, more effective, sustained, and transformative behavior changes may be possible ([Anderson et al., 2019](#)).

Further research is needed to help reshape initiatives within time and resource constraints. Relevant research questions include: how can initiative planners identify places in a system where small interventions will bring about large changes ([Meadows, 2008](#)), for instance, by creating feedback of interdependent self-reinforcing responses ([Duru and Therond, 2015](#))? Are there key behavioral changes of specific actors that can trigger a cascade of behavioral changes?

Finally, we call for additional research on collective behavior change processes and collective opportunity spaces. The notion of a collective opportunity space as provided by the ACT framework seems to be a new concept, one that could be elaborated to unpack stakeholder processes, for instance, in the context of living labs or innovation platforms. There is a need to better understand how collective opportunity spaces emerge from the composition and interactions of actors and how power dynamics influence their development.

7. Conclusion

In this article, we advanced the conceptual thinking on agency and behavior in agri-food system transformation and demonstrated the utility of a framework that bridges behavior- and system-change perspectives. When initiative designers and implementers understand and engage with both individual and structural factors as well as a diversity of system actors, initiatives can more effectively contribute to agri-food system transformation.

Applying the ACT framework during the design of agri-food system interventions can strengthen the connection between an initiative’s TOC assumptions and social-science theories. It can facilitate the development of explicit behavior change pathways toward systems transformation. Fundamentally, the ACT framework supports engagement with a wider set of actors and a more deliberate assessment of the enabling environment and important structural factors enabling or impeding behavior change. This approach complements vision co-design, identifying targets and potential levers for change, and developing a clear TOC, including assumptions and rationales. Crucially, the ACT framework bridges the gap from behavior change to systems change, in which expanded opportunity spaces and agency may empower behavior change among diverse actors, whose collective efforts can induce structural change in support of a shared vision.

This framework provides important insights, too, for donors and decision-makers supporting agri-food system transformation. Taking a systems-level perspective on behavior change processes, particularly one that acknowledges actor power and agency, requires new ways of working. Initiatives will need a multi-sectoral scope and partnerships to foster conditions for agency and behavior change. Metrics for success need to shift beyond the adoption of innovations to capture actor power, opportunity space for change, and productive collaboration. Agricultural research and development actors must also be pushed to explore and better communicate intervention rationales that reflect the complexity of the systems they work in. With these changes, we may build more sustainable, equitable, and effective pathways to support agri-food system transformation.

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Visualization, Methodology, Investigation, Formal analysis, Data curation. **Thomas Falk**: Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Methodology, Conceptualization. **Anne Rietveld**: Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Project administration, Methodology, Conceptualization. **Véronique Alary**: Writing – review & editing, Visualization, Validation, Investigation, Data curation. **Vimbayi G.P. Chimonyo**: Writing – review & editing, Validation, Investigation, Data curation. **Aymen Frija**: Writing – review & editing, Visualization, Validation, Investigation, Data curation. **Nadia Guettou-Djurfeldt**: Writing – review & editing, Visualization, Validation, Investigation, Data curation. **Guillaume Lestrelin**: Writing – review & editing, Visualization, Validation, Investigation, Data curation. **Sonali Singh**: Writing – review & editing, Visualization, Validation, Investigation, Data curation. **Aurillia Manjella Ndiwa**: Writing – review & editing, Visualization, Validation, Investigation, Data curation. **Taurai Zingwena**: Writing – review & editing, Visualization, Validation, Investigation, Data curation.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.agry.2025.104399>.

Data availability

Data will be made available on request.

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