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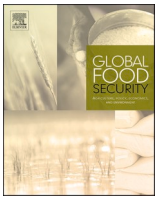

Enacting theories of change for food systems transformation under climate change

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ABSTRACT

In the past few years, we have seen growing calls for a transformation in global food systems in response to multiple challenges, including climate change. Food systems are responsible for a third of global greenhouse gas emissions from human activity and agricultural yields are at risk due to climate change impacts. Although many proposals have been made, there are fewer insights on what these imply for knowledge and innovation systems. We seek to advance the literature on transforming food systems under a changing climate, by identifying concrete next steps for scientists and practitioners. We do this by adapting a theory of change proposed by Campbell et al. (2018). We used the adapted theory of change to design the 5th Global Science Conference on Climate-Smart Agriculture, which brought together different stakeholders within global food systems. Through conference sessions and a survey with 262 of the participants, we validate elements of the Campbell et al. framework, identify additional elements, and offer further nuance. The findings point at nine priority areas for a transformation in food systems under climate change: (1) Empowering farmer and consumer organizations, women and youth; (2) Digitally enabled climate-informed services; (3) Climate-resilient and low-emission practices and technologies; (4) Innovative finance to leverage public and private sector investments; (5) Reshaping supply chains, food retail, marketing and procurement; (6) Fostering enabling policies and institutions; (7) Knowledge transfer; (8) Addressing fragmentation in the knowledge and innovation systems; (9) Ensuring food security. We have identified three types of scholarly insights from innovation, transition and sustainability transformations studies that may inform the next steps: these relate to stimulating novelty across the priority areas, ensuring participation in knowledge production, and reconfiguring incumbent systems to enable implementation of the theory of change.

1. Introduction

In recent years, there have been growing calls for a transformation in food systems. These calls have come from researchers, businesses, policymakers, civil society, amongst others. Various reports have highlighted this in the global arena (Pharo et al., 2019; Schmidt-Traub et al., 2019; Searchinger et al., 2019; Steiner et al., 2020). These calls for transformation are particularly relevant in the context of climate change, as food systems are responsible for a third of global greenhouse gas emissions from human activity (Crippa et al., 2021) and growth in agricultural yields may be affected up to 30% as a result of climate change, with the world's over 500 million small farms worst affected (GCA, 2019). Meanwhile, the world is not on track to eliminate hunger and 690 million people are undernourished while obesity is growing (FAO, 2020), even as 17% of food produced is wasted (Forbes et al., 2021), which shows inequities within food systems. The concept of transformation has different interpretations (Feola, 2015), but in common is a focus on fundamental changes that realise benefits for the environment and human well-being (Patterson et al., 2017), also referred to as 'system innovation'. System innovation is about

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comprehensive and co-evolving technological, institutional and social innovations which go beyond incremental innovations that optimize current systems but are aimed at radically reconfiguring systems (Barrett et al., 2020; Elzen and Wieczorek, 2005; Dentoni et al., 2017; Leeuwis et al., 2021; Meynard et al., 2017). Such system innovations may take several decades. In this paper, with the focus on climate change and food systems, transformation is seen as a change in at least one third of the inputs or outputs/outcomes of food systems, within 25 years or less (Vermeulen et al., 2018), as a result of system innovations.

Innovation processes (particularly system innovations) are thus key in catalysing a transformation in agriculture and food systems (Augustin et al., 2021; El Bilali, 2019; Leeuwis et al., 2021), and the literature indicates that for transformation it is important to be cognizant that innovation follows or is guided by directionality (Leach et al., 2020; Pigford et al., 2018). Such directionality of innovation comprises a certain value orientation (related to a certain problem framing and envisioned solution space – see Wanzenböck et al., 2020), and that can be enacted through different 'bundles' of technological, social and institutional innovations connected to transformative visions and concepts (Barrett et al., 2020; Klerkx and Begemann, 2020; Leeuwis et al., 2021). Such transformative visions, technologies, and concepts include for example agroecology, digital agriculture, vertical farming, cellular agriculture, and many more (see e.g. Herrero et al., 2020; Pigford et al., 2018), embodying different pathways to and envisioned outcomes of transformed food systems in terms of inclusive growth, social justice, resilience to climate change, biodiversity and other contributions to sustainable development (Hebinck et al., 2021; Herrero et al., 2021; Klerkx and Rose, 2020; Zurek et al., 2021; Chiles et al., 2021). Calls to transform food systems are accompanied by calls to transform knowledge and innovation systems (Barrett et al., 2020; den Boer et al., 2021; Fanzo et al., 2020; Fazey et al., 2020; Kok et al., 2019; Loboguerrero et al., 2020; van Bers et al., 2019) so that these better support food systems transformation and become 'mission-oriented' (Klerkx and Begemann, 2020). Mission-orientation of knowledge and innovation systems has become more prevalent recently in academic thinking and policy action and is about how innovation is framed in terms of its organisation, goals and purpose in view of systems transformation (Schot and Steinmueller, 2018). In the context of systems transformation (both in agriculture and food systems and for other systems such as energy, mobility, etc.), it has been argued that knowledge and innovation systems, beyond having a focus on linear technology transfer or orchestrating innovation for economic growth, need to be more explicitly supporting systems transformation and thus more strongly contemplate directionality towards this goal (Schot and Steinmueller, 2018; Pigford et al., 2018; Hall and Dijkman, 2019; Klerkx and Begemann, 2020; Leeuwis et al., 2021). Knowledge systems are made up of different players that generate, transform, transmit and store knowledge (Foray, 1997), while innovation systems take a wider lens and include the policies, institutions, cultural factors and power dynamics that more broadly play a role in the development and adoption of a novel technology or practice (Klerkx et al., 2012), e.g. related to resources exchange for innovation and creating of legitimacy for new technologies and practices. Thus, knowledge systems are an important part of innovation systems.

Transformation of these knowledge and innovation systems is particularly relevant in food systems, as around USD 56 billion is spent every year on agricultural research and development (R&D) (Fuglie et al., 2020), but they are sometimes focused on incremental as opposed to transformative change (Hall and Dijkman, 2019). Therefore, reorienting these investments to accelerate the transformation in food systems under climate change is a major opportunity (Steiner et al., 2020). There are growing calls to donors to double the investment into agricultural R&D (Alston et al., 2020) and to agricultural development as a whole (Laborde et al., 2020). However, several issues have been identified, especially in public agricultural research systems including poor scaling logic and directionality, lack of understanding of the role of the private sector, misleading narratives, short term funding cycles, fragmentation, poor evidence base to support transformation, insufficient focus on novel approaches and mission orientation (Hall and Dijkman, 2019; Klerkx and Begemann, 2020; Steiner et al., 2020). Therefore, there is an imperative to transform knowledge and innovation systems, in the absence of which a transformation in food systems will remain a distant dream as several connected changes are needed to break out of lock-in and path dependency situations (Conti et al., 2021; Leeuwis et al., 2021). Hence, here several bundled or coupled system innovations are needed (Barrett et al., 2020; Elzen and Wieczorek, 2005; Leeuwis et al., 2021; Meynard et al., 2017) in which both the food system and the knowledge and innovation system are simultaneously restructured and transformed (den Boer et al., 2021; Kok et al., 2019; Pigford et al., 2018).

Several recent studies connected to global agricultural research for development establishments, intended to inform policies on food systems transformation, have focused on the 'What', for food systems transformation (Barrett et al., 2020; Campbell et al., 2018; Herrero et al., 2020; Loboguerrero et al., 2020). For example, echoing earlier notions from agri-food innovation systems and transitions studies on the co-evolution of technology, practices and institutions (El Bilali, 2020; Kilelu et al., 2013; Klerkx et al., 2012; Leeuwis et al., 2021; Melchior and Newig, 2021). Barrett et al. (2020) have highlighted the importance of socio-technical innovation bundles for food systems transformation, Herrero et al. (2020) have identified innovations with transformative potential, and Campbell et al. (2018) and Loboguerrero et al. (2020) have identified priority areas for a transformation. However, a key knowledge gap remains around the 'How', i.e. how can a transformation be actioned based on priorities identified by prior work, and what does this mean for knowledge and innovation systems? Our research aims to address this knowledge gap, based on an assessment of stakeholder perspectives from those involved in agricultural research for development (AR4D). We have taken a theory of change approach to fulfil our research aim, using a theory of change proposed by Campbell et al. (2018), as part of the global initiative, 'Transforming Food Systems Under a Changing Climate',[1] which brought together over 100 organizations to develop a vision and action agenda for transformation. Section 2 introduces this theory of change (ToC) and Section 3 the methods. Section 4 subsequently examines the ToC with inputs from 262 key stakeholders, ranging from researchers, intermediaries, practitioners and users themselves. We enrich the priorities proposed by Campbell et al. (2018), further interrogate the findings with the literature to identify the next steps needed to transform food systems, using innovation as the key lever for change in Section 5 before concluding the paper in Section 6.

2. A theory of change to catalyse a transformation in food systems under climate change

A theory of change sets out an impact pathway for efforts to reach a logical set of outcomes or impacts based on the experience and expertise of those undertaking efforts (Thornton et al., 2017). The global initiative, 'Transforming Food Systems Under a Changing Climate' has produced several outputs in addition to its flagship report (Steiner et al., 2020). These include peer-reviewed and grey literature on transformation of food systems. A key paper that set out the vision was Campbell et al. (2018), which proposed a ToC for a transformation of food systems, which envisages transformative action being taken in eight key areas: 1) strong farmer organizations and networking; 2) climate-informed advisories and early warning; 3) digital agriculture; 4) climate-resilient and low-emissions practices and technologies; 5) prioritisation and pathways of change; 6) credit and insurance; 7) expanded private sector activity and public-private partnerships, and 8)

[1] https://www.transformingfoodsystems.com/.

capacity and enabling policy and institutions (Campbell et al., 2018). These priorities set out by Campbell et al. (2018), have been central to the development of the initiative, and Thornton et al. (2018) set out likely outcomes across each of these eight areas. Moreover, commissioned reports and related papers on specific action areas have also been produced as part of this initiative such as Herrero et al. (2020); Millan et al. (2019); Rawe et al. (2019); Stringer et al. (2020); Vermeulen et al. (2020).

In line with emerging experience in AR4D contexts, practitioners are using the ToC to develop context-specific approaches to food systems transformation, e.g. the Global Commission on Adaptation (Lobo-guerrero et al., 2018; Thornton et al., 2019) and the Green Climate Fund (GCF, 2020). Given the growing convergence between the scientific and practitioner communities around these elements, we proposed this theory of change to the advisory committee of the 5th Global Science Conference on Climate-Smart Agriculture (CSA), as the framework for designing the biennial conference that brings together the community working on interrelated issues of climate change, agriculture and food security. The committee, which was composed of scientists and practitioners, reviewed the theory of change, and based on their deliberations, a set of six refined elements were finalised as themes of the conference. These six themes are shown in Fig. 1, which are based on Campbell et al. (2018) and is the adapted theory of change we applied in this study. The elements of the theory of change are closely interlinked, and a transformation is envisaged as a coordinated set of efforts across these elements.

3. Methods

In essence, we introduced the theory of change proposed by Campbell et al. (2018), in the context of the 5th Global Science Conference on CSA, refined it based on inputs from the advisory committee, resulting in the revised framework (Fig. 1), which represents the current mainstream reasoning of professionals working on climate change, agriculture and food security. We interrogated the framework with conference participants through thematic discussions and a survey (Appendix 1). We also secured participants' inputs beyond the framework through open-ended questions, and built on these results based on the literature and propose ways forward to action a transformation in food systems.

The biennial Global Science Conferences on Climate-Smart Agriculture (CSA) bring together stakeholders working at the interface of climate change, agriculture and food systems issues. The first such conference was held in 2011 in the Netherlands, the second in 2013 in the United States of America, the third in 2015 in France, the fourth in 2017 in South Africa, and the fifth conference in 2019 in Indonesia (GCSA, 2019). The 5th conference had a specific focus on transformation of food systems and applied the framework (Fig. 1) in its design. This was done by making each element in the framework a theme of the conference, and contributions were secured through an open abstract submission process, thematic discussions were led by experts on each theme, and internationally renowned experts were also invited to make contributions along these themes. The conference brought together 410 stakeholders from over 200 institutions, based in 60 countries, thus bringing a wide cross-section of stakeholders (Dinesh, 2019).

Fig. 1. Theory of change for transforming food systems under climate change, based on Campbell et al. (2018).

The key stakeholders in the knowledge and innovation system may be grouped into researchers, practitioners and policymakers (Ingram, 2018; McCullough and Matson, 2016; Pingali and Kelley, 2007). We categorized conference participants into four categories: (1) primary knowledge producers such as CGIAR centres and programs, advanced research institutions, National Agricultural Research Systems (NARS); (2) knowledge intermediaries such as United Nations agencies, Non-Governmental Organizations, and consultancies; (3) knowledge users such as Government agencies, farmer organizations, and investors; and (4) beneficiaries of knowledge such as farmers and businesses that benefit from applying knowledge generated which reach them through intermediaries and users of this knowledge. Besides being knowledge producers, intermediaries, users and beneficiaries, these actors also fulfil wider roles in innovation systems, e.g. setting innovation policies, fostering innovation networks and platforms, and providing financial resources for innovation (Klerkx et al., 2012). We undertook a survey with the participants of the conference (see Appendix 1), and received 262 responses. 66% of the respondents categorized themselves as primary knowledge producers, 16% as intermediaries, 15% as users, 2% as beneficiaries, and the remaining categorized themselves as other. 19 of the respondents also indicated secondary categories in addition to the primary categories.

The responses have been analysed and results are presented in this paper. We complemented this with participant observation (Guest et al., 2013), using the lead author's role as a key organizer of the Conference, thereby gathering insights not only from the conference discussions, but the preparations including design, interactions with the advisory committee, and delivery of the conference. Due to the institutional affiliation of the authors, we can be considered grounded scholars and reflexive practitioners, both at the same time. In addition, we also bring insights from thematic discussions during the conference through the conference summary based on inputs from the leads of the different thematic discussions.

4. Results

Results are structured across four parts. In the first part, we present respondents' perspectives on the biggest issues facing the knowledge and innovation system, presenting results to an open-ended question on the topic. This is followed by results pertaining to the conference themes, where we not only present the priorities based on a ranking exercise but also further nuances within these priorities based on perspectives from the respondents as well as the conference summary. Thirdly, we present results on key factors that limit interaction among the different players within the system, which arise from an open-ended question on this issue. Finally, we set out the priorities for food systems transformation which emerge from the survey and conference discussions.

4.1. Biggest issues facing the food knowledge and innovation system

Based on our open-ended question to identify the biggest issues in the

food knowledge and innovation system, the respondents proposed up to 3 of the biggest issues. A total of 629 issues were identified, which we coded into 10 categories, while six of these categories correspond to the six themes identified in Fig. 1, the key additional themes identified include knowledge transfer, fragmentation in the innovation system and lack of systemic research, issues pertaining to food security, and 'other'. These additional themes are further considered in 4.10 as we seek to inductively identify priorities for food systems transformation. Fig. 2 provides an overview of all themes, including the percentage of mentions.

4.2. Priorities across themes

Among the six themes that were proposed to respondents, the theme on 'Climate-resilient and low-emission practices and technologies' was identified by 34% of the respondents as the most important theme. This was followed by 'Empowering farmer and consumer organizations, women and youth' (23%), 'Fostering enabling policies and institutions' (15%), 'Reshaping supply chains, food retail, marketing and procurement' (11%), while 'Digitally enabled climate-informed services' and 'Innovative finance to leverage public and private sector investments' received 9% of the respondents' priority (as shown in Fig. 3).

4.3. Empowering farmer and consumer organizations, women and youth

23% of the conference participants ranked empowering farmer and consumer organizations, women and youth as the highest priority. We received 138 responses on key areas for research, and inductively we found the focus was on ensuring access to resources and technologies (33%), the inclusion of different stakeholder groups (24%), capacity building (21%), business and funding models (8%) and developing a suitable enabling environment (8%). We also received 115 responses on key areas for action, while the areas converge with those for research, the priorities varied, with the highest priority for capacity building (32%), followed by developing a suitable enabling environment (25%), ensuring access to resources and technologies (14%), inclusion of different stakeholder groups (12%), and business and funding models (10%).

Outcomes of thematic discussions around this theme at the conference (Dinesh, 2019) show that empowerment of farmers and consumer organizations, women and youth, requires an explicit focus on realising equitable outcomes, and stakeholders need to shift beyond business as usual approaches, e.g. of collecting gender-disaggregated data, to an approach that addresses inequality explicitly, for example by ensuring women's access to technologies, services and information. The role of both formal and informal innovation platforms (Schut et al., 2019) that connect women farmers with men farmers and formal institutions and the private sector was also noted and is an area that requires more attention.

4.4. Digitally enabled climate-informed services

9% of the respondents indicated digitally-enabled climate-informed services to be the highest priority. Among the 51 responses received on key areas for research, we inductively identified focus to be on disruptive technologies and big data (35%) followed by generation of lessons from the application of digital tools (26%), the application of digitally enabled climate-informed services to extension (22%), and early response systems (14%). In terms of action, of the 44 responses received, the highest priority was accorded to the application of digitally enabled climate-informed services to extension (48%), followed by disruptive technologies and big data (23%), generation of lessons from the application of digital tools (21%), adaptive safety nets (5%), and early response systems (2%).

Thematic discussions at the conference highlighted evidence generation on both success and failure of digital agriculture initiatives by credible institutions and facilitation of knowledge sharing as key priorities (Dinesh, 2019). Knowledge sharing efforts can range from validation of claims around success of digital agriculture interventions, information sharing, and curation of complex scientific information, to address the diverse needs of stakeholders ranging from small to large farmers, private companies, Governments etc. Bundling of services, including climate, seed, fertilizer, credit, insurance etc., was identified as a preferred option for the private sector.

4.5. Climate-resilient and low-emission practices and technologies

34% of the respondents indicated climate-resilient and low-emission practices and technologies to be the highest priority. Among the 200 responses received on key areas of research, we inductively identified the focus to be on innovative scaling and capacity building (32%), generation of lessons from application (26%), context-specific support (15%), creating a suitable enabling environment for scaling (14%), and a focus on emerging innovations (10%). In terms of action, we received 174 responses, and the priorities differed. Respondents identified creating a suitable enabling environment for scaling as the most important area of action (36%), followed by innovative scaling and capacity building (34%), generation of lessons from application (13%),

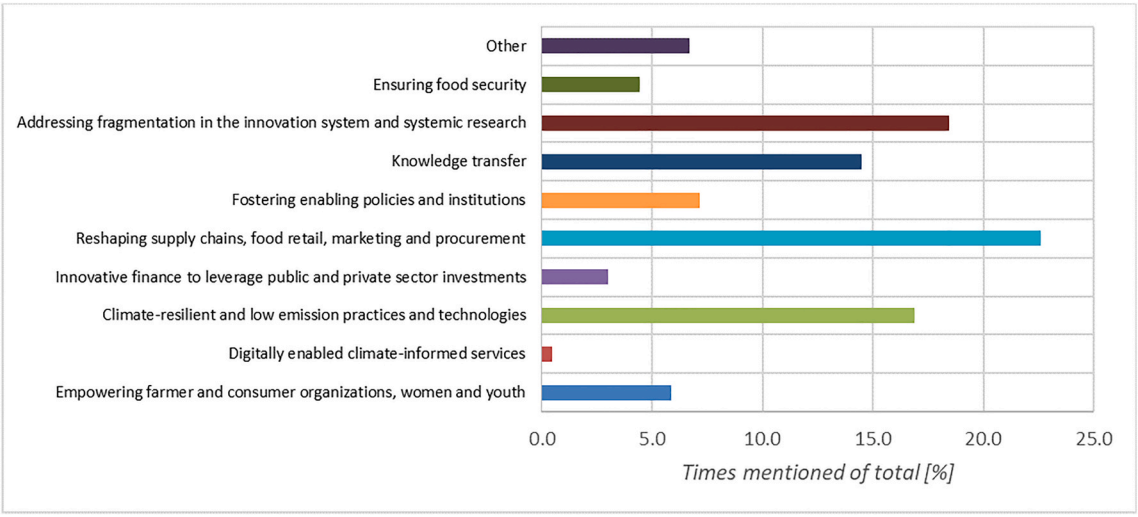

Fig. 2. Inductively categorized priorities for the food knowledge and innovation system.

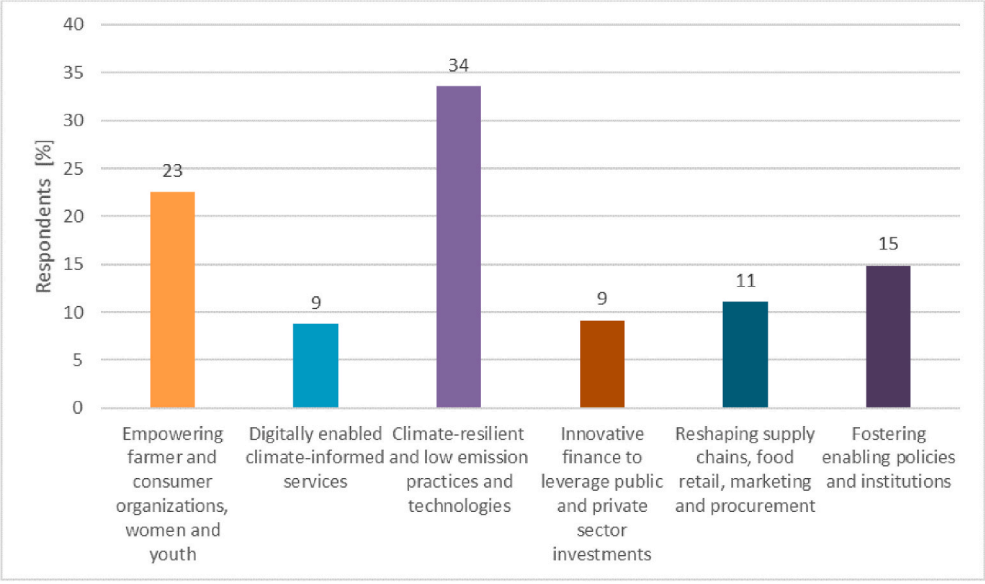

Fig. 3. Most important themes to catalyse a transformation in food systems.

context-specific support (8%), and a focus on emerging innovations (4%).

Thematic discussions at the conference noted that technologies and practices need to be implemented as part of a suite of interventions, which address the challenges and barriers of uptake to fulfil their potential in terms of scale (Dinesh, 2019). It was also found there is a need for further awareness-raising and training of both farmers and consumers, policy support, knowledge on costs and benefits, and to align agendas so that promising interventions can be scaled rapidly.

4.6. *Innovative finance to leverage public and private sector investments*

9% of the respondents indicated innovative finance to leverage public and private investments to be the highest priority. From the 52 responses received on key areas for research, we inductively identified the focus to be on approaches to mobilize the finance needed for transformation in food systems (54%), establishing incentives for technology uptake (19%), improving monitoring, reporting and verification methods (14%) and mechanisms to de-risk private capital (8%). 43 responses were received on areas for action, and show different priorities. Mobilizing the finance needed for transformation in food systems remained the highest priority (51%), establishing incentives for technology uptake was the second priority (16%), followed by improving monitoring, reporting and verification methods (14%), and mechanisms to de-risk private capital (12%).

The conference summary noted that knowledge gaps limit the ability to evaluate the bankability and impacts of projects, and need to be addressed to mobilize finance. Currently, knowledge is also fragmented at different scales, with uneven access. Improving accessibility and addressing fragmentation is an opportunity, particularly through digitalization, which can also improve the measurement of impact, which is important to investors. In addition, behaviour change among farmers, measurement of co-benefits and incentives are other key priorities (Dinesh, 2019).

4.7. *Reshaping supply chains, food retail, marketing and procurement*

11% of the respondents indicated reshaping supply chains, food retail, marketing and procurement to be of the highest priority. From the 63 responses on key areas for research we inductively identified the focus to be on new models of business-to-business coordination (25%), new diets and consumer choices (19%), market regulations (19%), realising efficiency gains in the supply chain (18%) and efforts to reduce food loss and waste (6%). In terms of action areas, from the 56 responses, market regulations were identified as the highest priority (32%), followed by new models of business-to-business coordination (30%), new diets and consumer choices (18%), realising efficiency gains in the supply chain (5%) and efforts to reduce food loss and waste (2%).

While the conference endeavoured to take a food systems perspective, considering downstream activities in the system including retail, marketing and procurement, the focus of discussions were primarily on reducing food loss and waste (FLW) and changes to diets (Dinesh, 2019). There is a need to take a systemic perspective, and consider issues including behaviour change, trade, health, common definitions and systemic interventions.

4.8. *Fostering enabling policies and institutions*

15% of the respondents identified fostering enabling policies and institutions to be the highest priority. 90 responses were received on key areas for research, and we inductively identified the focus to be on governance issues and reforms to address inequities (38%), innovative approaches to policy design and implementation (31%), incentives for CSA (16%), and a focus on participatory approaches (12%). In terms of action, we received 84 responses, and governance issues and reforms to address inequities remained top priority (32%), followed by participatory approaches (31%), innovative approaches to policy design and implementation (19%), and incentives for CSA (16%).

During thematic discussions at the conference, it was found that policies and institutions need to transform from providing technical solutions to providing solutions that are relevant to specific farming circumstances, enabling farmers to improve their livelihoods (Dinesh, 2019). Top-down policy-making was identified as a concern and deterrent to the adoption of innovations. Knowledge systems need to tackle issues including the reforms needed to improve the livelihoods of farmers, livelihoods-based research at the farm level, more effective science-policy interfaces, and a systemic approach to issues.

4.9. *Factors that limit interaction among different players in the knowledge and innovation system*

Based on a question to identify the factors that limit interaction among different players in the knowledge and innovation system, a total of 475 factors were identified and inductively coded. . The key issue

identified by respondents was around fragmentation of efforts (42%). These ranged from competition among institutions, a project-oriented approach etc. The other key factors included the culture of research and development (24%), equity within the knowledge system (22%), and the absence of long term thinking and implementation (10%). Respondents noted several features in the culture of research and development including in communicating and disseminating research results, in partnering, and in doing outcome-oriented research as deterrents to improving interaction among players. It was also noted that the different players within the system are often unequal in terms of power relations, and this needs to be explicitly addressed for transformation. Efforts are also needed to foster long term thinking while designing research efforts, which also complement implementation efforts.

4.10. Priorities for food systems transformation

We hypothesised that to transform food systems under climate change, we need to catalyse research and action in the key areas set out in the framework (Fig. 1), some of which pertain more to the food system, while others are more connected to the knowledge and innovation system, In practice, they are often coupled (Kok et al., 2019). Based on the survey responses, we now get further nuance on actions within these areas, as well as three additional inductively derived categories, namely: improving knowledge transfer, addressing fragmentation in knowledge and innovation systems, and addressing food security issues. Based on stakeholder perceptions we can identify not only the broad-based priorities but also more specific areas of focus for research and action (Table 1).

5. Discussion

5.1. Unpacking priorities for food systems transformation

There is a growing focus on proposals to transform food systems to achieve food security (Caron et al., 2018), which requires a food systems approach to research and action (Fanzo et al., 2020; Ingram, 2011; Reardon et al., 2019; Steiner et al., 2020). The priorities which have been validated, identified and elaborated in this paper (Table 1) further confirm the importance of a food systems approach and provide elements for a theory of change to catalyse a transformation under climate change. Taking action along these priorities would require moving outside disciplinary silos, towards the common goal of achieving food security under a changing climate. The elements proposed in this theory of change can facilitate such transdisciplinary work based on key stakeholder-driven priorities. Within different priorities, sometimes the emphasis is more on food system change itself (e.g., how it is organised, the role of diets, the role of novel technologies), and sometimes the focus is more on how to organize for change (e.g., how to organize for knowledge exchange, mobilize finance).

On food system change itself, the theory of change prioritises the empowerment of farmer and consumer organizations, women and youth (Campbell et al., 2018) specifically around ensuring a strong voice for local organizations and stakeholders. Action and research in this area can build on earlier work on the role of civil society and grassroots organizations in transitions related to sustainability (El Bilali, 2019; Hermans et al., 2016), as well as on different adaptation and development pathways for different types of farmers (Stringer et al., 2020). These efforts are important in the context of the role of power and governance in transformations (Dentoni et al., 2017; Patterson et al., 2017).

Digitalization has emerged as a key enabler for transformation in different sectors, economies, and businesses, and can enable food system change too. However, agriculture as a sector is behind others in the application of digital tools and services, which is a key opportunity for transformation (Klerkx and Rose, 2020; Shepherd et al., 2020), but challenges may be encountered especially in low-income countries where the scaling of digital tools is limited by the challenges faced by farmers (Bacco et al., 2019; Deichmann et al., 2016), capacity and investment gaps (Hinson et al., 2019). More research and action on the application of digital tools can help address these challenges and enable the transformation in food systems. In addition to digital tools, a wide array of technologies and practices are available which can accelerate

Table 1
Priorities for research and action under a new regime for innovation.

Element of the theory of change	Priorities for research and action
Empowering farmer and consumer organizations, women and youth	- Inclusion of different stakeholder groups. - Ensuring access to resources and technologies. - Creating a suitable enabling environment for empowerment. - Building capacity to empower stakeholders. - Business and funding models to empower stakeholders.
Digitally enabled climate-informed services	- Generation of lessons from the application of digital tools. - Identifying and implementing disruptive technologies and big data approaches. - Provision of digitally enabled climate-informed services and extension. - Early response systems and adaptive safety nets.
Climate-resilient and low-emission practices and technologies	- Generate lessons from the application of technologies and practices. - Innovative approaches to achieving scale and building capacity. - Identifying and implementing emerging climate-resilient and low-emission innovations. - Provision of context-specific support for CSA. - Creating a suitable enabling environment for technology implementation.
Innovative finance to leverage public and private sector investments	- Approaches to mobilize finance for transformation. - Innovative financial mechanisms to de-risk private capital. - Identifying and providing incentives for technology uptake. - Improving approaches for monitoring, reporting and verification.
Reshaping supply chains, food retail, marketing and procurement	- Developing and implementing new models of business-to-business coordination. - Supporting new diets and consumer choices. - Efforts to manage food loss and waste. - Generating efficiency gains in the supply chain. - Market regulations to reshape supply chains, food retail, marketing and procurement.
Fostering enabling policies and institutions	- Innovative approaches to policy design and implementation. - Governance and reforms to address inequities in the food system. - Participatory approaches to policy design and implementation. - Incentives to scale CSA.
Knowledge transfer	- Improving approaches to dissemination and communication. - Enabling access to knowledge through user-oriented language, content, and products. - Translation of scientific knowledge to support implementation.
Fragmentation in the innovation system and lack of systemic research	- Improving approaches to partner with stakeholders. - Changing the culture within research and development. - Addressing fragmentation and duplication that stems from competition.
Ensuring food security	- Attention to poverty alleviation as part of a transformation. - Addressing nutritional needs and hidden hunger.

such a transformation. These range from food production to diets and waste management (Herrero et al., 2020), and includes new and emerging technologies and practices which have transformative potential, such as artificial meat/fish, nano-drones, on-field robots, personalised food etc. (Herrero et al., 2020). Enabling adoption of such technologies and practices has transformative potential, but technological options need to be combined with social aspects (Barrett et al., 2020) and trade-offs and ethical concerns need to be addressed (Herrero et al., 2021; Klerkx and Rose, 2020). Experience from approaches like technology assessments and responsible research and innovation can help with this Klerkx and Rose (2020); Leeuwis et al. (2021); Rijswijk et al. (2021); Vanclay et al. (2013).

User-oriented research and action are needed across the food system, from farm to fork (Fanzo et al., 2020). This means a focus on actions beyond production, including supply chains, retail, marketing and procurement, diets, food loss and waste, and consumer choices (Loboguerrero et al., 2020; Vermeulen et al., 2020), which are key to food system change. Moving to healthy diets which enable us to remain within planetary boundaries (Willett et al., 2019) is a major area of opportunity, but requires deep structural changes in costing, policy, culture, equity and governance (Béné et al., 2020).

On organizing for change, while Campbell et al. (2018) set out priorities for greater private sector activity, credit and insurance, the stakeholder-based priorities suggest further streamlining and developing new pathways for innovative finance to leverage public and private sector investments. Financial flows have been affected by market failures including lack of a deep pipeline of bankable projects, aggregation mechanisms and matchmaking facilities (Millan et al., 2019). These are important areas to address through research and action, developing innovative mechanisms, incentives and investment models that can enable overcoming these market failures. An example is blending public and private finance to reduce risk and mobilize capital rapidly, as in the case of the Global Innovation Lab for Climate Finance and the Agri Business Capital fund (Zougmoré et al., 2021).

Sustainability transitions are highly political (Avelino et al., 2016), and structures of power and vested interests create path-dependency and lock-in situations which make incumbent systems inert and difficult to change (Conti et al., 2021; Leeuwis et al., 2021). Therefore, the political economy has been highlighted as a key area of research for a food systems transformation (Béné et al., 2020; Leach et al., 2020; Turner et al., 2020). Enabling policies and institutions can be achieved through innovative approaches to policy design, implementation, land governance and reforms, trade rules etc. Such innovative approaches grounded in science, enable more effective science-policy interactions. However, a profound understanding of knowledge transfer in the context of transdisciplinary research is still largely missing (Adler et al., 2018). Appropriate processing of results to address user needs, supporting intermediaries and context-specific awareness have been highlighted as approaches to improve knowledge transfer (Nagy et al., 2020). Enhancing credibility, salience, and legitimacy of knowledge production has also been noted to increase the effectiveness of knowledge production (Cash et al., 2003; Opdam, 2010). Furthermore, efforts need to go beyond linear approaches, taking cognizance of institutional, power and participation dynamics (Cvitanovic et al., 2015; Leeuwis et al., 2021; van Kerkhoff and Lebel, 2006) and how researchers must deal with these dynamics (Lahsen and Turnhout, 2021). Fragmentation of knowledge and absence of systems thinking has been noted as a key problem for sustainability transitions (Kok et al., 2019; Saviano et al., 2019), therefore efforts are needed to address such fragmentation through long term thinking, systemic research, efforts to address disciplinary silos and more streamlined funding.

5.2. *Actioning priorities for food systems transformation – next steps*

Our findings provide a clear signal that stakeholders working at the interface of climate change, agriculture and food systems issues see the need for innovation and food systems transformation. Insights from the findings and the literature on innovation studies suggest that this would require efforts along three areas to implement the revised theory of change. These are:

i) Stimulate novelty through niches

Novel approaches are needed within food systems, right from food production through to consumption. The priorities which have been identified (Table 1) provide areas to stimulate novelty through research and action. However, conscious efforts are needed to stimulate novelty in these areas to help catalyse a transformation in food systems aligned to the theory of change. To do this, knowledge and innovation systems need to change, and approaches such as strategic niche management (Kemp et al., 1998; Schot and Geels, 2008), wherein protected spaces are created to stimulate novel technologies or transition management where 'transition arenas' are created (Loorbach et al., 2017) are useful concepts. Strategic niche and transition management have a long tradition of application in agricultural transitions, including in the global South (e.g. El Bilali, 2020; Elzen et al., 2012; Hounkonnou et al., 2012), and could be extended to wider food systems (Leeuwis et al., 2021; Weber et al., 2020) and can inform underpinning knowledge and innovation systems (Meynard et al., 2017; Pigford et al., 2018). This would involve providing temporary protection or incentives for actions in the priority areas to stimulate novelty, which may come from different actors such as scientists, grassroots organizations, and start-ups, which challenge and contest current food system set-ups and propose (radical) alternatives (Herrero et al., 2020; Klerkx and Begemann, 2020; Leach et al., 2020). Such protection is needed to encourage investors and decision-makers to take risks to support such approaches which may often not be fully developed. These can include promoting the development and scaling of climate-resilient and low-emission practices and technologies, innovative financial mechanisms, approaches to scale digital solutions etc. Such extended application of strategic niche management can enable decision-makers to stimulate novelty across the priority areas.

ii) Ensure participation in knowledge production

While stimulating novel approaches, it is essential for knowledge and innovation systems to be inclusive of stakeholders within food systems, including farmers, consumers, women and youth. Prior work (Brown et al., 2018; Kilelu et al., 2013; Leeuwis et al., 2021; Samian et al., 2016) has shown the crucial role of farmers in sustainability transitions, and in the face of climate change, it is anticipated that different types of farmers will need to follow different adaptation and development pathways (Stringer et al., 2020), and novel approaches need to be brought to farmers along these pathways. Novel approaches are also needed to bring capacity building and funding to enable farmers to take pathways that are climate resilient and generate lower emissions (Taneja et al., 2019). In addition to farmers, the role of consumers is also crucial (Vermeulen et al., 2020) while taking a food systems approach. To gain the trust of stakeholders, knowledge generated should be relevant to their needs, credible and legitimate (Cash et al., 2003), this means that structural changes are needed to the knowledge and innovation systems to ensure that these attributes are reflected in knowledge generated (den Boer et al., 2021; Kok et al., 2020)(den Boer et al., 2021; Kok et al., 2019). Good examples of ensuring participation can be seen in the growing emphasis on citizen science that bridges the gap between science and society and improves impact (Sauermann et al., 2020) and in science-policy engagement efforts (Dinesh et al., 2018), but efforts need to go beyond individual research projects or organizations to realise changes at the food system level (Turnhout et al., 2021).

iii) Reconfigure incumbent systems

As noted in the introduction, the current knowledge and innovation

system already faces several challenges including poor scaling logic and directionality, lack of understanding of the role of the private sector, misleading narratives, short term funding cycles, fragmentation, poor evidence base to support transformation, not sufficient focus on novel approaches and mission orientation (Hall and Dijkman, 2019; Klerkx and Begemann, 2020; Steiner et al., 2020). Therefore, a reconfiguration does not mean only addressing new areas (e.g. by stimulating niches), but also addressing structural issues in the current food system as well as knowledge and innovation system which may also be an effort including incumbent players (Conti et al., 2021; Turnheim and Sovacool, 2020). A food systems approach requires action from production through to consumption, and this implies both stimulating novelty but also phase-out of some activities across the system (Klerkx and Begemann, 2020; Leeuwis et al., 2021). To do this, knowledge and innovation systems that cover different parts of the food system need to be reconfigured to address the goals of transformation, and integrated to stimulate novelty and organize phase-out across the system as opposed to only parts therein (Hall and Dijkman, 2019). While this is challenging, our results indicate that the community working across climate change, agriculture and food systems is cognizant of the need for change, which provides fertile ground for reconfiguration. This means that traditional disciplinary boundaries need to be surpassed so that innovation from the production end through to consumption are brought together. This will mean reconfiguring knowledge and innovation organizations to step up to this challenge. For example, the CGIAR is the international system for agricultural research, our findings point that organizations like the CGIAR need to move outside their comfort zones, which is in its legacy of crop breeding and the green revolution (Dinesh et al., 2021).

However, reconfiguring incumbent systems through disruptive innovation and phase-out will lead to winners and losers, as has been noted in the context of global change (O'Brien and Leichenko, 2003). Resistance may be encountered from the incumbent system (Conti et al., 2021; Smink et al., 2015), and this will need to be addressed (Herrero et al., 2020). It has been argued that through leadership and incentives (Dinesh et al., 2021), a reflexive approach (Sundbo and Fuglsang, 2006), and a mission-oriented approach to innovation (Klerkx and Begemann, 2020), it is possible to address such resistance. This would involve making contestation, negotiation and (productive) conflict more explicit part of the scope of innovation processes (Skrimizea et al., 2020; Turner et al., 2020). To track progress in this change process, not only is rigorous monitoring needed of how food systems transformation progresses in different dimensions of sustainability and thematic areas (Fanzo et al., 2021; Hebinck et al., 2021), but also of how the knowledge and innovation systems that support this transformation develop (den Boer et al., 2021; Klerkx and Begemann, 2020; Kok et al., 2019).

6. Concluding remarks

Last year, the UN Secretary General, Antonio Guterres said, *"Our food systems are failing, and the COVID-19 pandemic is making things worse"*, and he called for a transformation in food systems to make these systems more inclusive and sustainable (UN, 2020). The Secretary General convened the first of its kind Food Systems Summit to take transformative action. This is not simple and comes with political challenges not only in preparations but also in delivering the ambitions through appropriate accountability mechanisms (Covic et al., 2021; Turnhout et al., 2021). In this context, building on the global initiative on 'Transforming Food Systems Under a Changing Climate', there is an opportunity to catalyse a transformation. However, a key knowledge gap remains around the 'How', i.e. how can a transformation be actioned and what does this mean for knowledge and innovation systems? We sought to address this knowledge gap by collecting and analysing insights of people working in the domain of AR4D, food systems, and climate change, thereby linking with the lived reality of practitioners.

In line with emerging experience in AR4D contexts (Douthwaite and Hoffecker, 2017; Maru et al., 2018; Thornton et al., 2017), AR4D practitioners are using ToCs to develop context-specific approaches to food systems transformation, and in this paper, we find that enacting a theory of change for food systems transformation under climate change can be an effective way to catalyse a transformation and we set out the key priorities for a theory of change. These priorities are placed within the broader perspective of knowledge and innovation systems, and we identify the next steps for better developing the new, reconfiguring the old and making knowledge generation more participative. For each of these three next steps, we can draw on valuable insights as developed in adjacent bodies of literature on innovation systems, system transition and transformation, and science-policy interactions.

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.

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Appendix A. Supplementary data

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