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How to swarm? Organizing for sustainable and equitable food systems transformation in a time of crisis

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ABSTRACT

Accelerating food systems transformation in the face of climate change and other global crises requires myriad changes across all levels, themes, and geographies. This calls for re-thinking the roles of agricultural research for development (AR4D). In this perspective article we use the metaphor of 'swarms' and 'swarming' to illustrate a more distributed way of working with a set of approaches that, if implemented jointly, may help AR4D researchers and their institutions to step up the pace and scale for food systems transformation, as urgently called for in global dialogues around the UN Food System Summit, COP 26, and beyond. We identify four roles for AR4D within swarmed design: facilitating the directionality of swarms, fostering swarm mentality and creativity, engaging with swarms in different innovation spaces, and building up and monitoring swarm intelligence. Enacting these roles would require an enabling environment, with the main food systems actors working together in four priority areas: aligning allies around shared visions and innovation portfolios, coupling tailored funding schemes and reworked incentive systems, building more permanent spaces for boundary work, and exploring new ways for structuring science.

1. Introduction: Swarming to support transformation of food systems

'The house is on fire! Telling people to look for the exit signs will be more effective than trying to organize all in a disciplined descend (Kurtz and Snowden, 2003).'

There is no doubt about the urgency to transform our food systems in the light of accelerated climate change and other global crises (Webb et al., 2020). Now that climate action is increasingly becoming a matter of self-interest for many countries and stakeholders (Hancock, 2019), we may have arrived at a critical moment where transformative change is possible (Gotts, 2007), driven by collective will (Loboguerrero et al., 2020).

With food systems we mean the network of actors and activities that interact with one another, within an ecological, social, political/cultural, and economic environment, in relation to growing, processing, distributing, consuming, and disposing of foods, from provision of inputs to waste and recycling (Ericksen, 2008). The action areas for achieving the Sustainable Development Goals (SDGs), which are seen as key outcomes for food systems transformation, in fewer than ten years, are outlined in numerous reports (e.g., Béné et al., 2020; Herrero et al., 2020) and inform recent global calls for action (von Braun et al., 2021) and installation of global science-policy interfaces for food systems (Turnhout et al., 2021).

But can such high-level collective action alone catalyze sustainable and equitable food systems transformation? First experiences are mixed at best (Canfield et al., 2021), with a lack of agreement among scientists, policy makers and field-level practitioners on how the changes needed are to be achieved (Zurek et al., 2021). Although some argue for structured global networks with a central role for agricultural research for development (AR4D) institutions (Béné et al., 2019), food systems are highly diverse and context-specific (Gaitán-Cremaschi et al., 2019), and agri-food system transitions must deliver against a complex suit of goods and services, with multiple objectives, trade-offs and conflicts between the different public- and private-sector actors along food supply chains, and in an environment that is rapidly changing (Dentoni et al., 2017; Klerkx and Rose, 2020). This results in multiple visions of future food systems (Zurek et al., 2021) which do not necessarily align (Wojtynia et al., 2021). In fact, it has been argued that transitions and transformations cannot be centrally steered (Scoones et al., 2020), and that

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multiple transition pathways play out simultaneously (El Bilali, 2019a; Klerkx and Begemann, 2020). Coordination therefore must be based on adaptive management of collective action of multiple actors (Klerkx et al., 2010; Leeuwis et al., 2021) so that 'individual, uncoordinated actions occur as if they were carefully choreographed' within different transformation pathways that each have their own 'bundles' of innovations (Barrett et al., 2020).

In the context of AR4D and agricultural innovation systems, the notion that innovation can only be partly planned and takes place in self-organizing systems has been recognized earlier (Ekboir et al., 2013; Klerkx et al., 2010; Spielman, 2009), but here analysis and action were often focused on particular technology or practice development processes. In view of the multiple simultaneous innovation and change processes need for food systems transformation, we therefore propose that the concept of 'swarms', 'swarming' and particularly 'swarm intelligence', can have value to better grasp, facilitate and choreograph interactions among AR4D and other actors. Also, it can help clarify the roles AR4D can play in food systems transformation which involves multiple changes at multiple scale levels (field, farm, territory, country, region, global level).

Swarms and swarming have been described from different science and engineering disciplines such as biology, mathematics, behavioral science, and robotics, and capture the self-organizing nature and emergent behavior of systems that are central in complexity perspectives on innovation, transition, and transformation (Loorbach et al., 2017; Olsson et al., 2014; Pyka and Küppers, 2002). For this paper, the focus is on swarm intelligence: inspired by natural swarms, the concept of swarm intelligence describes the collective behavior of decentralized, self-organized entities that can move quickly in a coordinated manner (Beni, 2009). This focus on decentralized and self-organized entities connects with adaptative and reflexive approaches to research, design and innovation which allow for re-design of systems, experimentation with novel and emergent designs, and scaling of fit-for-purpose and fit-for-context designs, as widely applied in transition and transformation science and practice (e.g. transition management, strategic niche management, large systems change, reflexive interactive design, transdisciplinary research, blended portfolios of impact investments – see Apampa et al., 2021; Dentoni et al., 2017; Elzen and Bos, 2019; Loorbach et al., 2017). While swarming is increasingly being explored as a concept for designing societal responses to wicked problems (Roggema and Van Den Dobbelsteen, 2012; Tan et al., 2008), it has not yet been applied to reflect on the role of AR4D in food systems transformation and how AR4D should be organized for this purpose.

AR4D has been experimenting with forms of participatory research through multi-stakeholder approaches (e.g., innovation platforms, citizen science) and design-oriented science (e.g., development of new ready to use products) to support innovation relevant for achieving the SDGs for decades already (Berthet et al., 2018; Dalrymple, 2008; Kristjanson et al., 2009; Leeuwis et al., 2018; Schut et al., 2016; Spielman, 2006; Sumberg et al., 2013; Sumberg and Reece, 2004; van de Gevel et al., 2020). However, the durable institutionalization of participatory research and design-oriented approaches in AR4D remains a challenge (Kristjanson et al., 2009; Schut et al., 2018). In the context of food systems transformation, we can safely assume that this requires new sets of skills and forms of coordination for AR4D (following Dinesh et al., 2021b) which need further development and support. Applying the notion of 'swarm intelligence' could help to illustrate what types of approaches need to be implemented jointly to address some prevailing key questions and tensions of sustainable development at the scale of food systems transformation:

- How to catalyze large-scale collective action with a shared directionality, while accommodating different perspectives and pursuing different transition pathways?
- How to foster outcome-oriented collective action across multiple scales in an efficient and equitable way?
- What enabling environments would be needed to support such 'swarmed design' approaches?

In view of these questions, here we reflect on the concepts of 'swarm' and 'swarming' as metaphors to illustrate emerging new roles of AR4D in food system re-design and transformation. We conclude with four priority areas in which policies, funding mechanisms and incentive systems could work together to create the enabling environment needed.

2. Coupling design and swarm principles

Earlier work in the context of AR4D acknowledges the relevance of participatory and design-oriented research and innovation principles such as developing a shared vision and direction, incorporating different stakeholders' views and iterative feedback loops in the development of appropriate technologies and practice by AR4D (Berthet et al., 2018; Elzen and Bos, 2019; Kristjanson et al., 2009; Meynard et al., 2017; Schut et al., 2016; Sumberg et al., 2013), and these continue to be promoted in AR4D institutions (e.g., Govaerts et al., 2021). These also play out, albeit on larger scales, in food systems transformation. In Table 1 we couple the main design principles relevant for food systems transformation with the principles of swarming, to illustrate a more 'swarmed' way of working, which might help AR4D institutions and relevant food system actors unleash the many changes needed at all scales.

2.1. Self-organization around multiple attractors for food systems transformation

The principle of facilitating a shared vision, while integrating different perspectives (i.e., multiple transition pathways) presents a central challenge. There will always be different ideas on how

Table 1
Applying swarming principles to the main design-oriented principles relevant for food systems transformation.

Main swarming principles of natural or human or artificial swarms		Main design-oriented principles relevant for transformation	
Occurrence	Principles	Principles	Occurrence
Natural swarms (Brown et al., 2014; Ray and Liew, 2002)	*Self-organization*: Swarmed around attractors, no (permanent) leadership	Shared vision, integrating different perspectives	**Design principles relevant for SDGs** (Maher et al., 2018)
	Swarm optimization: marked by robustness, resilience and adaptivity	Maximizing synergies, minimizing compromise	
	Swarm communication: simple and easily understood information	Visualization	
Human swarms (Gloor, 2006, 2017; Wall and Mitew, 2018)	*Swarm mentality*: Diversity Trust Creativity	Transdisciplinarity across scales	**Additional principles of human- or nature centered design** (Beckman and Barry, 2007; Brenner et al., 2016; Liedtka et al., 2018; Micheli et al., 2019; Thakur et al., 2021)
	Empathy Agency Autonomy	Empathy and experiential learning	
Human and artificial swarms (Fleischer, 2003; Holden et al., 2017; Wubben et al., 2021)	*Swarm intelligence*: Shared memory based on rapid feedback loops and error discovery	Rapid prototyping and testing, (failing), and iteration	

transformation should happen. Many AR4D institutions avoid taking clear advocacy positions (Leeuwis et al., 2017), not sharing a single narrative themselves and for example committing to a system such as agroecology (Hauser, 2020), and there is indeed a tension between roles of impartial scientist and a more engaged activist researcher (Milkoreit et al., 2015; Wittmayer and Schäpke, 2014). In this process, AR4D can articulate alternative futures and the implications of different choices (see e.g. Zurek et al., 2021; Herrero et al., 2021), since swarms do not have to follow a (permanent) central lead. While natural swarms may be guided by different aims such as reproduction, search for food and defense, they follow the principle of self-organization, organically forming around attractors (Brown et al., 2014).

Two reflections derive from this. First, the principle of self-organization illustrates how AR4D, politics and powerful market players (including the donor community) can create a mutually reinforcing dynamic around attractors (e.g., by science informing funding agencies, which in turn direct and attract more science), eventually crowding out alternative views and approaches (Clapp, 2021; Lahsen and Turnhout, 2021). This may lead to myopia and the risk that only selected transition pathways are chosen which may even lead to further-lock in (Conti et al., 2021; Vanloqueren and Baret, 2009). Second, however, a swarmed form of design could also point to a more distributed set-up, potentially involving local actors and user communities which otherwise would not be reached (Berthet and Hickey, 2018). In the context of food systems transformation, attractors could be alliances or coalitions of interest, guided by shared value creation or missions (Gloor, 2017; Hall and Dijkman, 2019; Klerkx and Begemann, 2020; Wall and Mitew, 2018), emerging leadership networks (e.g. the Transformation Leaders Network of the World Economic Forum), grassroots movements such as those for agroecology (Hauser, 2020), or new trends such as those presented by Agriculture 4.0 (Klerkx and Rose, 2020) representing technological trends such as digitalization and cellular agriculture (Antonacci et al., 2017; Gloor et al., 2009; Herrero et al., 2020). For example, the Global Commission on Adaptation undertook a one-year convening involving 23 countries, hundreds of advisers and research and action partners, that jointly formulated a set of outputs that resulted in heightened political visibility of adaptation. Moreover, the outputs of the Commission resulted in increased funding commitments to a range of multi-sectoral, practical actions, many of which are now being implemented in a self-organized way (GCA, 2019).

2.2. Swarm optimization to address different levers and levels of food systems transformation

While the notion of connecting local, regional and local networks pursuing a similar goal in a mission-oriented way has been articulated before (Klerkx and Begemann, 2020), food systems are complex and boundaries are fuzzy. The principle of swarm optimization may show how different swarms could navigate complex global challenges in an efficient way: with no or no permanent leadership, natural swarms rely on local interaction of individuals and their next neighbors (Holden et al., 2017). This mechanism also allows swarms to split up and continue independently, when encountering an obstacle (Fleischer, 2003; Wubben et al., 2021). Complexity for each individual may thus be reduced, and pathways become more serendipitous, adapted to local conditions. Translated to human swarms, the principle of swarm optimization can make swarmed networks highly efficient, robust, and resilient in dealing with obstacles and adverse conditions (Gloor, 2017). This is akin to the design principle of maximizing synergies while minimizing compromise. In the context of food systems transformation, the swarm metaphor may illustrate how swarmed networks in different local conditions, responding directly to urgent local needs and challenges, could still collaborate or work in a complementary way towards shared impact, for instance by addressing or creating different system leverage points (Abson et al., 2017). For example, with the aim of addressing systemic market failures that prevent sustainable finance from achieving relevant impacts for food systems transformation, the CGIAR research program on Climate Change, Agriculture and Food Security (CCAFS) and its partners, including 35 leading public and private financiers, developed a road map with detailed short-, medium- and long-term strategies that can be applied by governments, public and philanthropic investors, corporate investors and private financial investors (Limketkai et al., 2020). This illustrates how many different individuals with different perspectives and working along different transition pathways can still move towards a shared overall goal – in effect, operating as a swarm.

2.3. Swarm communication across different knowledge systems

Closely allied with the swarm principles of self-organization and swarm optimization outlined above is the principle of swarm communication, reflected in the design principle of visualization, suggesting the use of representations that foster mutual understanding such as boundary objects (Klerkx et al., 2012), visualizations and story-telling (Akama et al., 2019). Because swarms are kept together by the communication of their entities with their next neighbors (Wubben et al., 2021), information needs to be simple and meaningful, to be easily understood (Ray and Liew, 2002). Translated to human swarms, this would mean the transparent sharing of accessible knowledge (Gloor, 2006) and the integration of different forms of knowledge, such as tacit (Almeida et al., 2009) and indigenous knowledge (Makondo and Thomas, 2018). For example, some countries in the global South have become innovation hubs by necessity and can inform global policies with their experiences in climate adaptation (Mcleod et al., 2019).

Although there are increasing efforts to include different kinds of knowledge (e.g., a focus on valuing indigenous knowledge systems in the dialogues around 2021's UN Food System Summit), especially with regard to agri-food sustainability transitions, there is a strong bias towards representations of authors from the North (El Bilali, 2019b, 2020; Melchior and Newig, 2021; Weber et al., 2020). The swarming metaphor here emphasizes the need to connect different types of knowledge and knowledge systems, which leads back to the questions of who informs (and thereby guides) the different swarms, and what could be the role of AR4D institutions in this. We return to this issue in section 3.

2.4. Swarm mentality towards shared value creation

The design-oriented principle of transdisciplinarity (Köppen and Meinel, 2015; Micheli et al., 2019) has been recognized as an important element for identifying solution-oriented approaches to transformational change in sustainability transitions, as it contributes to addressing the root causes of unsustainability (Abson et al., 2017). Here we use the term transdisciplinarity to describe collaboration across different knowledge paradigms and across all food system actors. Developing and scaling socio-technological innovation bundles for food systems transformation (Barrett et al., 2020) requires the 'co-evolution of actors, institutions, networks and knowledge' (Boyer, 2020; Herrero et al., 2021). Related design principles that can reveal and address the root causes of problems are empathy and experiential learning (Beckman and Barry, 2007; Micheli et al., 2019). As a long history of participatory and co-creation approaches in AR4D has also shown (see e.g. Neef and Neubert, 2011; Schut et al., 2018; Van de Gevel et al., 2020), a lack of empathy with stakeholders or what also have been called the 'problem, knowledge, and solution holders' will likely lead to innovations that are mistargeted or result in inaction (Berenguer, 2007; Jackson and Payne, 2020; Jagers et al., 2020), making empathy a key ingredient for sustainability and transitions towards transformed food systems (Berenguer, 2007; El Bilali, 2020; Francesca et al., 2021).

Here, the added value of the swarm metaphor is twofold. First, it re-emphasizes the need for a distributed set-up to avoid spatial, temporal or causal separation of the designers (e.g., researchers, companies) from the problem holders (e.g., local communities, policy makers), which can lead to detachment and ineffective solutions. Second, it emphasizes that empathy and multi-stakeholder experiential learning are closely related to skills and tacit knowledge, which are necessary to build and maintain innovation capacities at all levels (Ganguly et al., 2019). The principle of swarm mentality, used mainly in the context of human swarms, is geared towards shared value creation, based on empathy, agency and autonomy within the shared values (Gloor, 2017; Khan et al., 2018; Marcus et al., 2014). Individuals' agency is strengthened by rotating functions and distributed responsibilities of swarm leaders and members (Antonacci et al., 2017), so that the diversity of entities within a swarm is highly valued (Krause et al., 2011), which consequently builds individual skills through experiential learning (Khan et al., 2018). This in turn increases members' motivation (Gloor, 2006) and fosters the trust- and experience-based relationships (Marcus et al., 2014) needed to develop deep empathy and unleash swarm creativity (Gloor, 2006). One example that comes close to illustrating swarm mentality is CCAFS: a tight, globally-distributed network of hundreds of participants organized into small, autonomous teams, with highly-focused intermittent interaction, working successfully for more than a decade via common impact pathways and theories of change (Haman and Hertzum, 2019; Nowak et al., 2021). Such impact pathways and ToC then need to embrace complexity and learning to be effective, to translate and enhance connections between different levels of action (global-local) and foster deep engagement (Douthwaite and Hoffecker, 2017; Thornton et al., 2017).

2.5. *Swarm intelligence to accelerate innovation and scaling*

A main design-oriented principle for accelerating the process from innovation to impact is applying a series of simple but rapid steps of prototyping and testing to obtain timely feedback for iterations (Maher et al., 2018). In relation to human or artificial swarms, the principle of swarm intelligence can be used to describe how 'rapid error discovery and fast feedback loops are emergent functions of a distributed content production process, leading to incredible fluidity and adaptability' (Wall and Mitew, 2018). This can be achieved by making work sharable in architectural layers (Frein, 2016) and by acting in more open innovation systems (Berthet et al., 2018; von Hippel, 2009) in which innovations not only use building blocks that are already available but also produce spin-offs that can be used again by other parties (Bogers et al., 2018). For example, the World Bank's portal on climate smart agriculture (https://www.worldbank.org/en/topic/climate-smart-agriculture) contains an online guide for targeting and prioritizing climate-smart technologies and practices, offering tools tailored to different stakeholders and user groups (from farm to landscape levels, market actors or regional, national and global policies) which can be used in complementary ways. Climate-smart country profiles can be complemented by country investment profiles or scaled down to community adaptation plans, for instance. Pioneered by CCAFS, the World Bank and partners, these tools are now being utilized and further developed by many other actors such as FAO, the African Agriculture Initiative, and USAID's Bureau for Food Security. There are further several examples of interoperable knowledge and data tools being used by multiple partners in broad alliances that aim to identify levers for, and monitor progress towards, food systems transformation. These include the CGIAR Big Data Platform (https://bigdata.cgiar.org/), the Innovative Food Systems Solutions portal of the Global Alliance for Improved Nutrition (https://ifssportal.nutritionconnect.org/), the Commission on Sustainable Agriculture Intensification (https://wle.cgiar.org/cosai/), and the Digital Agri Hub hosted by Wageningen University & Research (https://digitalagrihub.org).

3. Discussion: embracing different roles of AR4D for 'swarmed design' in food systems transformation

Several authors have highlighted the key role that AR4D can play in contributing to novel agricultural and food systems taking a design approach (Berthet et al., 2018; Elzen and Bos, 2019; Meynard et al., 2017; Sumberg and Reece, 2004). A 'swarmed design' approach to AR4D may involve relatively new roles for researchers and AR4D institutions (Fig. 1), which we discuss below.

3.1. *Facilitate the directionality of swarms, addressing different levers of food systems transformation*

Since swarming behavior is largely dictated by circumstance, AR4D institutions can play a crucial role in facilitating and perhaps orchestrating the directionality of different swarms. They can help to assess and diagnose current global crises, and build the development pathways that lead towards common visions of what future food systems should look like, by using the tools and methods of participatory scenarios, for example (Pereira et al., 2020). This also includes formulating research questions that underpin and inform dialogues around what are the 'right' things to do (Hauser, 2020), thus helping to negotiate or accommodate contesting views.

Especially in the context of food systems transformation, AR4D deals increasingly with questions of societal desirability and social license (Barrett et al., 2020). Crucial here is to give voice to people who will feel the effects of global crises most (Rossi et al., 2019) to enable a fair and just transition (Robinson and Shine, 2018). In the context of food systems transformation, swarmed design initiatives could eventually arrive at targeting poverty and inequality, which are recognized as major underlying factors of our global crises (Boyce, 2018; Klenert et al., 2020). AR4D could then play a role in unveiling the power dynamics that oppose or accelerate system transformation (Clapp et al., 2018; Crawford and Andreassen, 2015), for instance by increasing transparency about innovations, evaluating risks and unintended consequences (Wigboldus et al., 2016), and tracking and communicating the distribution, flow and consumption of resources.

3.2. *Engage with swarms in different innovation spaces for different purposes*

Scientists have increasingly been engaging in co-designing agricultural innovations with non-academics (Norström et al., 2020), whereby AR4D institutions combine expert roles with facilitating or brokering collaborative processes (Wigboldus et al., 2016). AR4D institutions could complement such efforts by engaging and partnering more strategically with networks and initiatives active in the different areas of food systems transformation (Béné et al., 2020) and in the different phases of the cycle of innovation, development and scaling (Sumberg et al., 2013). For example, Koerner et al. (2022) identified four innovation spaces in which different multi-stakeholder groups can play a role in articulating, designing, mainstreaming or creating the enabling environment for innovations. Thus, social movements and consumer organizations can feel the pulse of current trends and articulate and amplify demands (Nature Food, 2020). Spaces for multi-stakeholder experimentation that rapidly develop and test innovations (e.g., innovation platforms (Schut et al., 2018) and 'Living Labs' (Gamache et al., 2020; Kok et al., 2019; Toffolini et al., 2021)), can connect to larger, multi-stakeholder platforms such as policy networks that aim to level the playing field and business networks that provide more leverage (Schut et al., 2018).

Such systemic research and design approaches (Hall and Dijkman, 2019) are inherently unpredictable and call for flexibility (e.g., as in 'reflexive designs' (Elzen and Bos, 2019)), and for creating and using windows of opportunities (Klerkx et al., 2010). Funding initiatives would need to be designed accordingly, allocating time and resources to networking, joint agenda setting, and mutual learning; and allowing project goals and theories of change to be continuously adjusted (Dinesh et al., 2021c; Schneider et al., 2019; Thornton et al., 2017).

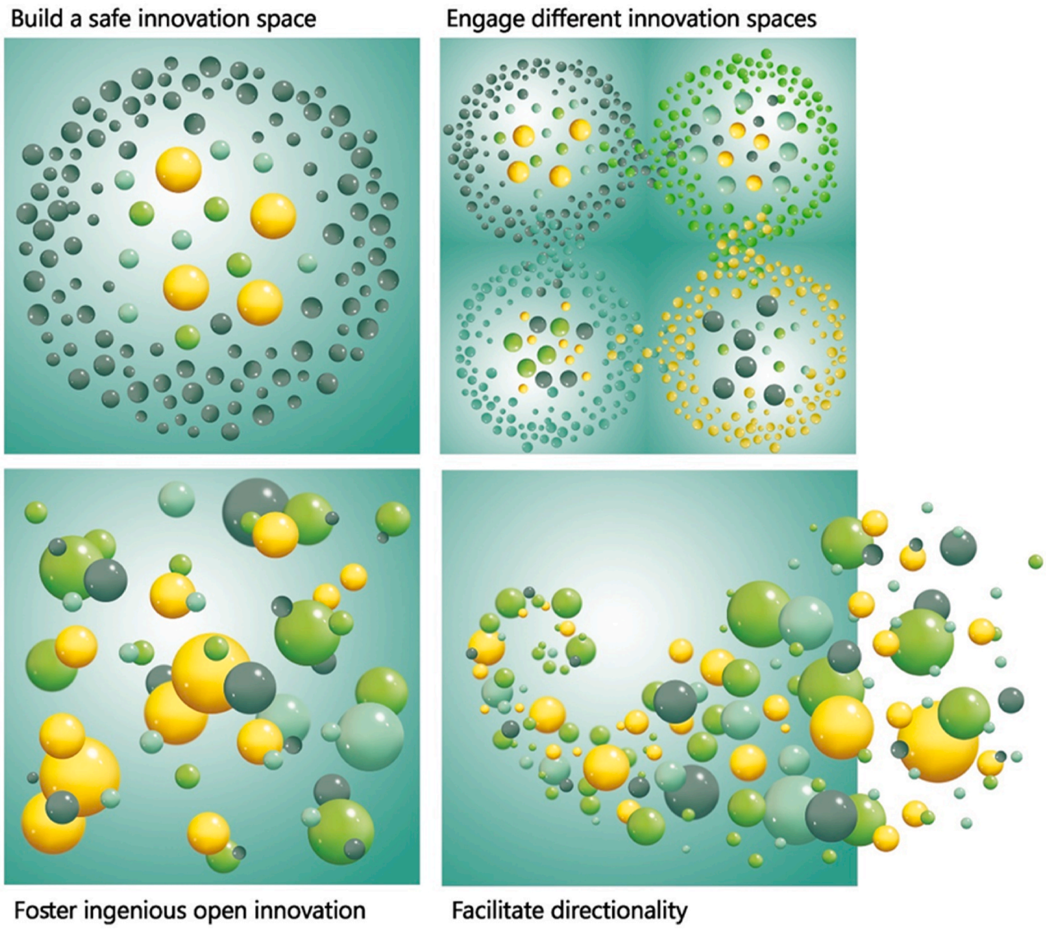

Fig. 1. AR4D roles for facilitating swarmed design.

3.3. *Foster swarm mentality by providing safe and continuous spaces for innovation*

AR4D institutions already employ methodologies of multi-stakeholder experiential learning that inherently promote empathy and transdisciplinary (Micheli et al., 2019), in the form of living labs (Toffolini et al., 2021) or climate-smart villages (Andrieu et al., 2019), for instance. However, with their focus on in-depth understanding and getting to the root causes of problems or of the motivations of key actors, rather than on representativeness and replicability, they can be at odds with a scientific culture that values hard facts (Sarwar and Fraser, 2019) or a metrics- oriented impact culture valued by funders. In addition, there are resource limitations in scaling such resource-intensive participatory approaches (Westermann et al., 2018), so that human- or nature-centered design approaches may sometimes be narrow in scope (such as focusing on the end user without considering value chain actors) or limited to more downstream applications and services such as climate information or financial services (Christel et al., 2018).

The swarm metaphor suggests that empathy and cross-disciplinary experiential learning thrive well in contexts that allow for or explicitly foster individuals' agency, autonomy, trust and creativity, with special emphasis on developing individuals' skills. This would point to a need for collaborative environments where experimentation with new configurations of social–ecological systems can occur, which Pereira et al. (2020) call transformative or 'safe enough' spaces.

Nevertheless, there are obstacles for developing such a swarm mentality directed towards societal outcomes that need to be addressed. For example, academic educational systems and research careers still disincentive young people to pursue positions that require inter- and transdisciplinarity (Koerner et al., in press), neglecting to build capacities to innovate and to manage change that can increase researchers' agency (Armstrong, 2016). To facilitate safe spaces around shared value creation (Gloor, 2006) in which researchers could easily switch between the roles of expert and learner (i.e., breaking the so-called expert-learner duality (Pugh and Prusak, 2013)), institutions could apply more reflexive and complexity-aware monitoring and performance evaluation systems (Douthwaite and Hoffecker, 2017) and increase appreciation of and response to failures (Dinesh et al., 2021a). This could take place in a context of AR4D institutions rethinking their incentive systems, towards rewarding pro-active (societal) problem-solving approaches and accountability (Arnott, 2021). Further, such safe spaces could also be more effective and permanent boundary organizations or brokers in AR4D, as argued earlier (Klerkx et al., 2009; Kristjanson et al., 2009; Pereira et al., 2020) and reiterated recently (Govaerts et al., 2021), connecting knowledge systems and food system actors and value chains across scales.

3.4. *Build up and monitor swarm intelligence by co-developing differentiated approaches to enable genuinely open innovation*

Cross-boundary sharing of knowledge and innovations is increasingly cited as an important key for enabling food systems transformation (Berthet et al., 2018; Dinesh et al., 2021c; Govaerts et al., 2021), with building up stocks of interoperable knowledge, data and best practices having been at the heart of recent global dialogues. A swarmed approach to design could help to prevent this from becoming a bottleneck for inclusion. AR4D institutions already employ open source processes such as citizen science (van de Gevel et al., 2020) and on-farm experimentation (Lacoste et al., 2022) as a way to make research more effective, democratic and accountable, and also for large-scale monitoring purposes, as in the Food Systems Dashboard (Chandler et al., 2017; Fanzo et al., 2020b). Such approaches would also need shared repositories of interoperable building blocks of knowledge, data and tools that speak to each other and are easy to use (Beza et al., 2017).

However, more open innovation approaches are not unproblematic in the AR4D context. Concerns range from the robustness of data, and consequent liabilities and reputational risks, to questions on intellectual property rights and non-disclosure agreements. One way to address such concerns could be to distinguish the potential uses and users of innovations, which might have quite different needs and risks associated with the quantity and quality of data (Clarke, 2016). Another way could be to differentiate between generic innovations and complementary new products or applications, which could provide both societal benefits and licensing opportunities, thus incentivizing public and private stakeholders alike (Ardito et al., 2020). Likewise, in some cases of downstream research such as the provision of climate services (Koerner et al., 2021), a more modular design approach may be appropriate (Brax and Toivonen, 2007; Habib et al., 2020). This would mean disaggregating and regrouping different components of innovations into modules, according to the components that interact most strongly (Ethiraj and Levinthal, 2005). Once such a modular architecture is established, products or services could be re-packaged or re-purposed quite quickly, thus multiplying the options offered to users while reducing complexity for the providers (Naik et al., 2020).

4. Conclusion: Priority areas to support a swarmed design approach for transforming food systems

We have used the swarm metaphor as an integrative concept to reflect on new ways of organizing for sustainable and equitable food systems transformation, and the emerging roles of AR4D in the re-design of food systems. Revisiting the main design principles relevant for food systems transformation with a swarming lens, we have illustrated a more distributed, 'swarmed' form of design that might help unleash the multitude of changes needed along multiple transition pathways in a more efficient and equitable way. While not all the principles of swarmed design are novel, the approach may promote more awareness of how AR4D can operate in large, multi-scale transformation processes.

This approach would certainly challenge current AR4D processes and institutional set-ups (Fanzo et al., 2020a), though not all the principles of swarmed design would necessarily need to be applied to generate agri-food system transitions. It is likely that there are other aspects and institutional mechanisms that could be connected to the swarming concept that we have not covered here. In addition, such changes would not happen overnight nor in isolation. Rather, they would be part of longer-term reforms of international AR4D (such as the One CGIAR reform) and national AR4D institutes (Reardon et al., 2019), addressing long-standing bottlenecks that AR4D faces in the context of food systems transformation. To jointly navigate such change, actors engaged in governing, funding, incentivizing and implementing our food systems transformation could work together on the following priority areas, which might be especially salient in the context of swarmed design:

- Underpinning shared visions at local, national and regional levels with reflexive theories of change, and coherent mission-oriented innovation portfolios (Klerkx and Begemann, 2020; Sartas et al., 2020) to enable 'bundled innovations' (Barrett et al., 2020) that are supported by partners with the respective social license (Hall and Dijkman, 2019) and funders with a shared directionality.
- Coupling funding schemes that respond flexibly to different stages of innovation development and scaling, allowing for networking, joint and iterative agenda setting, and mutual learning (Schneider et al., 2019), with reworked AR4D incentive systems that reward a pro-active approach to solving societal problems (Arnott, 2021; Dinesh et al., 2021c).
- Supporting and building more permanent capacities for boundary work (Klerkx et al., 2012; Kristjanson et al., 2009; Schneider et al., 2019), especially with the up-coming generation of scientists to be able to connect across science disciplines, actor groups in food systems and scales needed for swarmed design.
- Exploring new ways for structuring science, with knowledge, data and tools that speak to each other (Koerner et al., in press), and more systematized feedback loops (Sumberg and Reece, 2004) within iterative swarmed design processes.

This is a first attempt to introduce the 'swarm concept' and its relevance for AR4D. The concept has strengths, but also pitfalls: its application might create new uncertainties and overlaps, and in the initial stages of its application, it may not be efficient and effective. Also, it tends to view food systems transformation as a process of co-creation and co-innovation, whereas the antagonisms and power dynamics in food systems transformation also call for 'supporting, doing and forcing change strategies' (Dentoni et al., 2017). More work would be needed for its operationalization in practice and for testing its usefulness for supporting collaboration in innovation networks and initiatives across all scales and levels. The necessity of rapid food systems transformation surely heightens the need for novel approaches to AR4D, and swarming may offer useful mechanisms to increase cohesiveness and alignment of all actors working to address this most urgent of challenges.

Author contribution statement

Jana Körner: Conceptualization, Writing -original draft, review & editing. Philip Thornton: Writing – review & editing. Laurens Klerkx: Writing – review & editing.

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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