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A systemic, multidimensional and territorialized framework for assessing the adaptation potential of sustainable agrifood transitions: theoretical guidelines and exploratory insights from the metropolitan region of Chile

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Introduction: The urgency of responding to climate change poses new challenges for agrifood systems, both to make them more sustainable and neutral in terms of greenhouse gas emissions, meet carbon neutrality commitments, and promote their adaptation to a changing climate, while also promoting territorial resilience. In this context, fostering the transformation of traditional agriculture toward innovative models that promote the development and adoption of innovative and ecologically sustainable and resilient adaptation measures, mechanisms and processes becomes extremely urgent. Growing interest has been emerging around approaches and experiences to develop and assess barriers and opportunities for 'sustainable' agrifood transitions ('SAT'). Despite these developments, there is still a lack of an integrated and territorialized analytical framework to account for the potential of SAT to respond to the risks and challenges associated with climate change. In view of this, this paper proposes an analytical framework that hopes to integrate the previous advances around a robust, systemic, multisectoral and context-sensitive observation of the potential of SAT as a strategy to address climate change risks.

Methods: This framework articulates around four complementary analytical lenses: the 'risk' lens addresses the 'potential' need for adaptation (why do we need SAT?); the 'resilience' lens focuses on how SAT may reduce risk (what do SAT do?); the third, 'sociotechnical transitions', looks at potential opportunities and barriers for the adoption and scaling up of these practices (how can SAT occur?); finally, the socio-technical "imaginaries" lens sheds light on the perceptions, expectations and visions behind the SAT (what are they for?). These analytical frameworks will be exemplified through incipient research that applies these observation lenses with the Metropolitan Region of Santiago de Chile as a case study.

Results and discussion: This exploratory approach allows to illustrate the observation framework and generating initial hypotheses about the territory under study. This favors a more holistic and systemic view of food security and the different elements that can generate risks to it, or promote its resilience, from a systemic and territorial approach, helping to understand why the SAT are necessary and how they can become potential strategies to promote food security in a context of climate change.

KEYWORDS

food system, sociotechnical transition, theoretical framework, sustainable food agriculture, analytical framework

1 Introduction

Climate change is one of the main risks at the global level (WEF [World Economic Forum], 2022), with impacts already visible in all regions of the planet, including alterations in temperatures, precipitation, seasonality, water availability, and increased climate extremes, among others (Vermeulen et al., 2018). Even in the most optimistic scenarios, these effects will continue to intensify in the coming decades, affecting various dimensions of human well-being (IPCC, 2018, 2021, 2022).

In this context, agrifood systems are on the front line, expecting abrupt drops in food production, increases in production costs, higher food prices, and impacts on food security, especially in the most vulnerable populations (IPCC, 2022). Simultaneously, the sector is responsible for about 30% of annual greenhouse gas emissions (Clark et al., 2020), thus needing a combination of both climate mitigation and adaptation strategies (Serraj and Pingali, 2018; Jones et al., 2021), in a context where global hunger remains above pre-COVID-19 pandemic levels [Food and Agriculture Organization of the United Nations (FAO), International Fund for Agricultural Development (IFAD), United Nations Children's Fund (UNICEF), World Food Programme (WFP), & World Health Organization (WHO), 2024].

Given this, the shift toward more sustainable agri-food systems (hereafter, Sustainable Agrifood Transitions or SATs) has gained importance, which has been associated with a renewed emphasis on strengthening and recovering local strategies, short distribution circuits, and recombining traditional knowledge and new technologies (Grauerholz and Owens, 2015). This is especially true in Latin America, and particularly in Chile, where several studies have sought to understand the potential that these practices may have (Gaitán-Cremaschi et al., 2020; Henríquez-Piskulich et al., 2021) and the opportunities and challenges for their adoption. However, a better understanding of the dynamics and determinants of SATs is still needed (Grote et al., 2021; Belmin et al., 2023).

Our proposal aims to contribute to this development, proposing reflections that seek to generate a systemic and comprehensive approach to address the potential of SATs as adaptation strategies to climate change in a particular region. Importantly, our approach is grounded in methodological pluralism, recognizing that this purpose can and should be achieved by combining different methodological approaches, both qualitative and quantitative, which can in turn be informed by different theoretical backgrounds. Our proposed contribution to literature is combining what are today different strands of literature and their respective analytical frameworks into an interdisciplinary insight. To this aim, Section 2 briefly describes the state of the art, emphasizing existing advances and gaps. Section 3 introduces the framework, composed of four analytical 'lenses' to understand the potential and challenges of SATs: 'risk', 'resilience', 'transitions' and 'socio-technical imaginaries'. Section 4 illustrates this framework in the case of the Metropolitan Region, Chile, providing exploratory insights into what these 'lenses' can teach us about the potential of SATs to elaborate action strategies in this context. Finally, section 5 concludes by reflecting on the application potential of the proposed approach.

2 State of the art

As anticipated in the Introduction, the food issue has gained increasing interest in recent years and has been studied from different approaches (López-Giraldo and Franco-Giraldo, 2015). A variety of indicators exist in this regard, such as the Global Food Security Index (The Economist, 2020), undernutrition and overweight statistics from ECLAC (2020), and the indicators of the second Sustainable Development Goal, reported by Food and Agriculture Organization of the United Nations (FAO), International Fund for Agricultural Development (IFAD), United Nations Children's Fund (UNICEF), World Food Programme (WFP), & World Health Organization (WHO) (2024).

Traditionally, the predominant approaches in this field adopted a sectoral perspective, focusing especially on the economic food supply chain (from production to consumption), with less relevance given to environmental, social, or political aspects (Ericksen, 2008). Recently, however, there has been a growing recognition of the need for a broader view, extending the understanding of food systems to the whole set of interactions and dynamics that occur both in production systems and in their ecological and human environments, and that influence the production, distribution, or consumption of food (Esham et al., 2018; Niles et al., 2018; Zeuli et al., 2018). Thus, studies have been emerging that adopt a systemic approach toward these problems, trying to address different aspects of their complexity (Marchetti et al., 2020; Schneider et al., 2023).

Simultaneously, the need to analyze the links between food security, sustainability, justice in food provision and consumption has been recognized, considering the ecological and social limits of tolerance, particularly important in the context of climate change (Béné et al., 2019; Juri et al., 2024). Consequently, the analysis of potential failures in food production and distribution has started to also consider the eventual unavailability, stability or quality of energy and/or water resources (Brouwer et al., 2024), as well as the technical, social, governance, and financial barriers that may limit access to these resources (Willaarts et al., 2020). Thus, more cross-sectoral approaches have appeared, seeking to promote sustainable food production, water planning, and/or energy efficiency in a joint manner.

Simultaneously, in contrast to the often "macro" character of traditional analyses (national or even macro-regional scale), the need to look closer to the regional and local scale has become increasingly important to highlight the heterogeneous socio-cultural, ecosystemic and technological conditions that influence the capacity of local food systems to ensure food security conditions for the population in particular territories (Lamine et al., 2012; Penny and Beach, 2021). Different case studies show how territorial particularities influence the degree of risk and vulnerability of agri-food systems to climate change, as well as the possibilities they have to cope with it (Bernard de Raymond et al., 2021; Rochefort et al., 2021). Research on the impacts of climate change has gradually overcome the initial tendency to focus only on the study of agricultural yields, adopting more multidimensional and transdisciplinary approaches, integrating variables such as food prices, decreases in production, the consequences of mitigation policies, quantity of emissions, and ecosystem services, among others (Abbass et al., 2022; Mehrabi et al., 2022).

Lately, this shift in perspective has reached even mainstream food security agencies, such as OECD, FAO and UNCDF, which have started to address food security through territorial approaches, highlighting the importance of socioecological aspects (Hinrichs, 2016), governance, economic growth, poverty, inequality, and social policies (Cistulli et al., 2014), technological and infrastructure conditions (Moragues-faus et al., 2020), in addition to the importance of multiple household factors in facing consecutive crises (Berdegué et al., 2024).

Despite these developments, there is still a lack of an integrated and territorialized analytical framework to account for the potential of SATs to respond to the risks and challenges associated with climate change. In view of this, we hereafter propose an analytical framework that hopes to integrate the previous advances around a robust, systemic, multisectoral and context-sensitive observation of the potential of SATs as a strategy to address climate change.

3 Toward an observation framework: four lenses for a comprehensive and interdisciplinary analysis

As mentioned above, one of the key challenges to understand the potential of SATs is the need for the territorialization and interdisciplinarity of the analytical perspective. Territorialization here relates to the fact that territorial particularities influence the degree of risk and vulnerability of agri-food systems to climate change, the possibilities they have to cope with it, as well as the importance of local socioecological, technological, and infrastructure conditions on the suitability, feasibility, and desirability of a given transition pathway. At the same time, however, integrated and comparable frameworks are needed to deal with this problem, assess different solutions, and extract learnings from local experiences. We consider that the first fundamental step in this direction is agreeing on a minimum set of research questions that need to be asked in order to assess the adaptation potential of sustainable agrifood transitions.

Our contribution offers that by combining different systemic traditions, a conceptual-analytical framework can be derived to frame these questions and offer guidelines for methodological application (although we are not taking a stance here on specific methodologies, believing in methodological pluralism for these kinds of problem-situations). In this sense, we offer an observational framework that allows us not only to better understand SATs per se but also to further define what is meant by 'potential' for adaptation to climate change. To foster a more systemic and holistic understanding of this 'potential', we propose a framework of analysis that draws on developments elaborated in different fields of study and research approaches, which we summarize in the form of four 'analytical lenses' (Figure 1), to be detailed in the following sections.

Each 'lens' offers a different analytical question, in turn inspired by a different theoretical and analytical strand of literature; as the decision tree shows, these combine together into the overall analysis. In fact, in the face of the question of 'what is the potential of SATs for adaptation', the first thing we need to know is whether there is a need for adaptation: if the need is not there, it does not make much of a case for a potential role on adaptation. But if the need is effectively present, it may indicate which areas, or dimensions, require the most attention, thus bringing us to the next step. To understand this, the 'risk' lens (section 3.1) observes the potential and probable impacts that climate change may pose for agrifood systems and territories, as well as the drivers of vulnerability to said impacts. Ths, it helps us to understand 'why' (and in what contexts, with what priorities) SATs are a priority to cope with the phenomenon.

Moving on, the second question we need to ask is whether a proposed strategy for SATs is effectively targeting the variables or factors that the first step determined as more relevant, which is a key component of understanding the 'potential': if the specific strategy has a low expected impact on variables of vulnerability of resilience, and/or if there is a mismatch between what it targets and the ones that are more proprietary in a territorial context, then the potential is not there. In our proposal, this question is addressed by the 'resilience' lens (section 3.2), which provides us a set of potential pathways through which SATs may be able to reduce vulnerability or increase the adaptive capacity of agrifood systems from a socio-ecological perspective.

However, even if this alignment exists in terms of the 'focus' of the SATs, this still does not answer in terms of whether the strategy can effectively be able to answer the 'magnitude' of the risk. This is where the third question kicks in, examining the degree to which the strategy can be scaled up and comparing it to the 'size' of the risk that is affecting the territory; it may be the case that the SATs strategy will only be able to work in a niche, in an exploratory or pioneering way, which may be relevant to research or even advocacy, but not as a fully fledged adaptation strategy, or it may be able to feasibly be scaled but not at the speed, size, or cost that is required to respond to the risk. To explore this, the third lens, centered on 'socio-technical transitions' (section 3.3) offers a comprehensive approach to understand the different conditions that need to align if SATs are to develop their adaptive potential (3.3). Finally, if the strategy also makes this test, the last analytical lens poses the fundamental question of who is going to benefit from it and for what goals. Adaptation is an inherently normative and political affair, and some strategies may be overly good for the local economy but bad for the most vulnerable groups. If that is the case, we consider this fundamentally biased and reduces the potential of the SATs as an adaptation strategy, as adaptation should be people-centered and focused on the most vulnerable groups. To that aim, the fourth lens, socio-technical "imaginaries" (3.4), sheds light on the perceptions, expectations, and visions behind the SATs, what they hope to achieve, and who they seek (or not) to benefit, thus helping to understand the 'what for' (or for whom) behind their potential.

3.1 Why SATs? Security, risk and territorial vulnerability of agri-food systems

According to the risk framework already established by the Intergovernmental Panel on Climate Change (IPCC, 2014, 2022), the operationalization proposed by Eurac (2017), by CR2 (Urquiza and Billi, 2018), and by the research team in previous studies (Urquiza

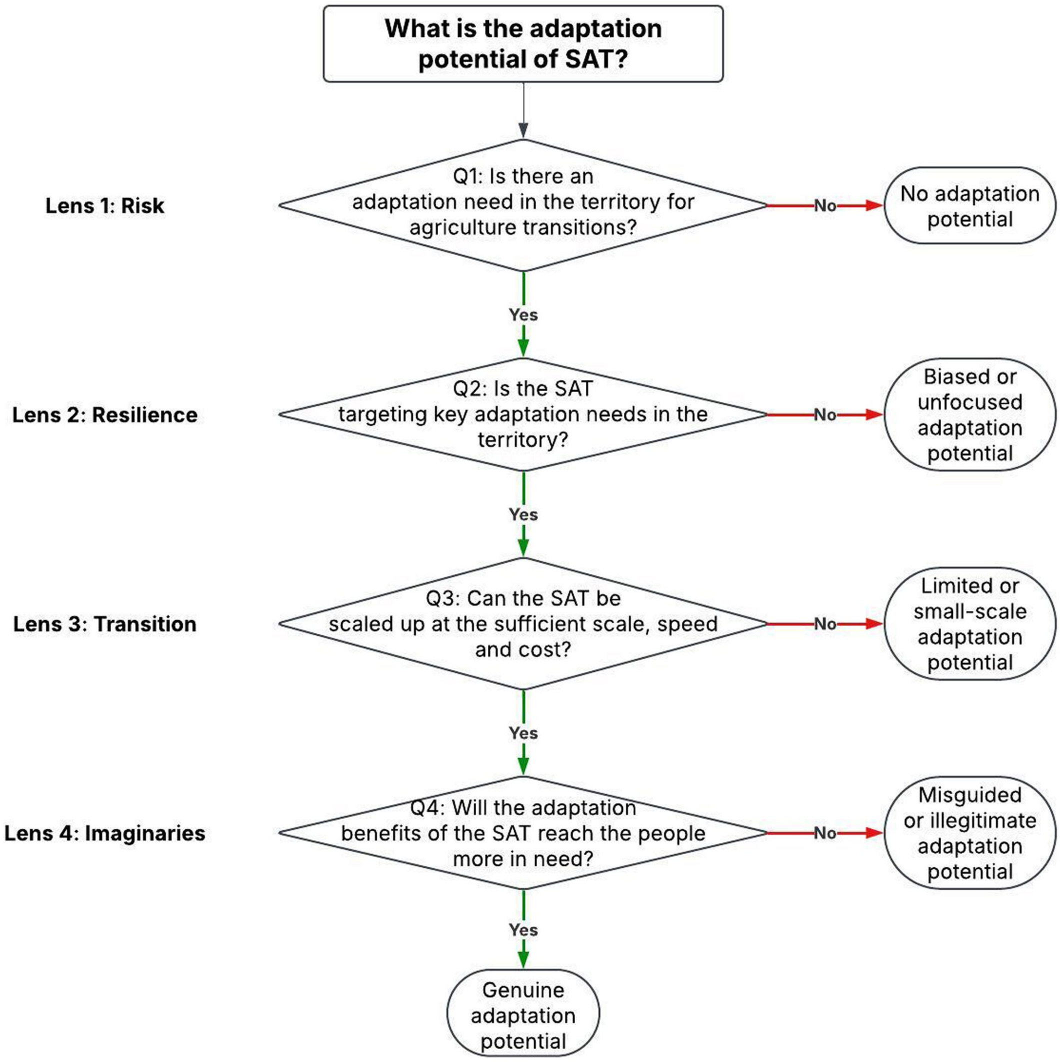

FIGURE 1
Analytical framework for SATs. Decision-tree integrating the lenses into an overall question on the adaptation potential of SATs.

et al., 2021; Billi et al., 2021), climate risk is understood as the probability of harmful consequences occurring within a given system or context (a productive sector, a community, a territory) as a consequence of events or processes associated with change. More specifically, this risk is a consequence of three factors: threat (probability and expected intensity of climate events), exposure (presence of elements or populations likely to be affected by these events), and vulnerability (predisposition or propensity of the system, territory, or population to be negatively affected by these conditions).

Applying this concept to agrifood systems requires defining what precisely is at risk. Risk can, for example, be defined in productive, economic, or social terms. Consistent with the approach adopted in this article, it will be convenient to focus on how climate change puts food security at risk, understanding this from a holistic and integral perspective. According to Food and Agriculture Organization of the United Nations (FAO) (1996), food security involves ensuring at least four conditions: food availability, access (including affordability), utilization, and stability. In order to operationalize these dimensions from a risk approach, which always implies a territorial dimension, in this article we will adopt this definition on the basis of previously advanced developments (Urquiza and Billi, 2020). Thus, we understand food security as the capacity of a territory to guarantee in a stable, sustainable, and resilient way the availability and equitable access to a quantity and quality of food that allows the human and economic development of its population. This definition requires the simultaneous achievement of two conditions:

i) **Availability and access in quantity and quality**: to offer equitable access to food in sufficient quality and quantity to satisfy the different utilization practices consistent with the human and economic development of its population.
ii) **Sustainability, stability, and resilience**: to ensure sustainability in the production, distribution, and consumption of these foods and their resilience and stability in the face of possible threats that could affect their supply.

In this sense, food insecurity will exist both when a territory is not capable at a given moment of ensuring the first condition. Also, when despite being able to do so, the future fulfillment of this goal is threatened by the lack of fulfillment of the second condition. The opposite may also be the case (a territory may have sustainable and resilient agrifood systems but not be sufficient to meet the needs of the population) or these two conditions may occur simultaneously, thus generating different degrees of security or insecurity.

Based on previous work (Urquiza and Billi, 2020; Amigo, 2019), we identify at least three types of processes that are relevant to consider for territorial security in the face of climate change, which are present in agri-food systems:

- Ecological processes, associated, for example, with hydrology, soil dynamics, climate, etc. They are fundamental to sustain food production, distribution, or consumption, and their failure can generate cascading effects on food security (e.g., desertification, the appearance of pests, effects on the water cycle, etc.).
- Technical processes, directly linked to the provision, processing, and distribution of food, so that their hampering has a direct consequence on food security.
- Sociocultural, associated with the different 'food environments' that may exist in each territory. Territorial environments refer to the interface between the food system and the consumer, composed of the different configurations of food availability, quality, affordability, forms of presentation, marketing, promotion, and front labeling of an item, type and proximity of places of food acquisition and consumption (from homes to fairs, supermarkets, and restaurants, etc.).

These three dimensions make it possible to identify specific elements of vulnerability, associated, for example, with the degree of 'health' or degradation of ecosystems and resource exploitation (ecological dimension), quality, age, and state of maintenance of infrastructure and technologies (technical dimension), and expectations, practices, and forms of organization of production, distribution, and consumption (socio-cultural dimension), which together determine the level of potential risk to which a territory's food security is subject in terms of the different climatic hazards that may affect it. Considering these different types of processes points to different 'paths' that risk can take with respect to food security, depending on the specific configurations of each territory and its populations and food environments.

3.2 What do SATs do for adaptation? Resilience potential of alternative agri-food practices

The concept of resilience has been gaining increasing recognition across multiple disciplines. Resilience reflects the capacity of individuals, communities, societies, and cultures to adapt and thrive with change in constantly changing environments (Folke et al., 2016). Likewise, this notion highlights crises as windows of opportunity, which recombine experience and knowledge, allow learning with change, and guide transformations toward more sustainable paths (Biggs et al., 2016). On the other hand, this school is concerned with the interrelationships between agency, networks, institutions, and innovation, paying attention to the emergence of new governance and management systems that can restore, sustain, and develop the capacity of ecosystems to generate essential services (Olsson et al., 2015). For these reasons, resilience scholars also pay attention to misalignments between environmental governance systems and ecosystem dynamics, which threaten to erode social-ecological resilience and push life-supporting ecosystems beyond critical thresholds into more degraded and less productive regimes (Cumming, 2011).

Finally, the approach highlights that while adaptation and resilience are latent properties, which can often only be fully understood when disasters occur (Smit and Wandel, 2006), it is possible to generate predictors that can guide a prospective view. Previous studies (Urquiza and Billi, 2018; Valencia et al., 2021; Urquiza et al., 2021; Billi et al., 2021) have made it possible to operationalize the idea of resilience in Chile in association with climate change in relation to three main dimensions: (a) flexibility, associated with the sufficiency, diversity and redundancy of the system's processes and resources; (b) its propensity to learn from past impacts, incorporating various types of formal and informal knowledge, in addition to adaptive behaviors and technologies; and (c) its capacity for self-organization and self-transformation, including the existence of local and polycentric forms of collective action and governance and coordination arrangements. During the last few years, progress has allowed specifying these dimensions in the form of indices (Billi et al., 2021) and attributes (Billi et al., 2024; Billi et al., 2023) that can serve as a proxy to define how certain concrete actions are making progress toward building more resilient systems, populations, or territories.

Based on the above, we can distinguish and specify how measures aimed at promoting food security can generate (or limit) resilience within different levels or domains (ecological, technical and socio-cultural). Likewise, practices that are positive for certain domains can be negative for others, while conversely, effects on the resilience of some can ultimately escalate into the potential collapse of others as well, if not managed in time. Regenerative agriculture, agroecology, and ecological intensification can provide promising results to promote the resilience of agrifood systems and thus reduce the risk to food security.

Existing literature provides quite convincing evidence regarding their impact, particularly on the ecological dimension. For example, its advantages include nutrient flow in agroecosystems, soil quality management, water and soil conservation, ecosystem integrity (Jakovac et al., 2021), and biological regulation (Begg et al., 2017). For example, it has been observed how increased heterogeneity provides essential resources such as food, shelter, and nesting sites, which are often lacking in managed landscapes, thus promoting beneficial diversity of natural enemies and pollinators (Díaz-Siefer et al., 2022; Olmos-Moya et al., 2022), while at the same time strengthening nutrient availability, plant growth promotion, and pathogen and pest control, among others (Molina-Montenegro et al., 2019; Vidal et al., 2022). In turn, it is expected that the above will also lead to increased carbon dioxide sequestration, improved water cycling, and strengthened ecosystem services, as well as health and vitality of agricultural lands (Newton et al., 2020; Schulte et al., 2022).

Preliminary evidence suggests that increases in the territorial heterogeneity, natural areas conservation, and land sharing approaches would increase functional diversity and contribute to the stability of productive ecosystems (Tscharntke et al., 2021). Generating development plans capable of promoting agroecological agriculture would contribute to regulate air, water, soil, and climate quality

(White, 2011), as this type of agriculture generates healthy and biodiverse habitats (Gaytán et al., 2018), quality services, and sustainable microclimates that remove CO2 and reduce heat islands (Hoinle, 2016). They will also contribute to energy production, nutrients, efficient water use, income, health, and environmental stability (Molina et al., 2015; Minocha et al., 2017; De Wekker et al., 2018).

Likewise, evidence indicates that integrating agroecological food systems in urbanized contexts promotes food resilience of the population (Blay-Palmer et al., 2021; Bulgari et al., 2021), fosters sustainable urban development plans (Barthel et al., 2019), and decreases pressure on water supply in peri-urban and urban areas by "planting" (Attwater and Derry, 2017) and "recycling" (Mngumi, 2020) water in the city.

However, less evidence exists on how these practices may in fact impact the sociocultural domain of food security. Also, fully understanding how these 'potentials' manifest (or not) in practice in each context requires a careful and territorialized look at each case study. Our framework aims to guide such studies in a relatively 'standardized' way, which may favor the comparability and robustness of these assessments.

3.3 How may SATs occur? Opportunities and challenges for the socio-technical transition to sustainable agri-food systems

While the previous evidence displays the resilience potential of SATs, most refer to niche or pioneering projects. To fully understand the potential of SATs as an adaptation strategy, it is necessary to comprehend the possible pathways and challenges associated with their adoption at scale. In turn, understanding this cannot be limited to looking at purely technical or technological factors. Literature on 'socio-technical systems' has conceptualized productive systems and their innovations as a set of partially autonomous but interrelated elements and processes that intervene at different scales in the development of innovation processes and socio-technological change (including, for example, technologies, regulations, practices, markets, cultural meanings, and distribution and support networks; Miller et al., 2015; Valencia et al., 2021).

This change emerges from iterative processes of variation, selection, and retention, depending on existing social and technical structures (Geels, 2011, 2019). Often, these processes of structural change work on multiple levels, depending on the interaction between niches (protected spaces where innovations occur), regimes (semi-coherent sets of rules and structures that provide stability to systems), and landscapes (variables and trends that change slowly and influence socio-technical actors, but are invariant in the short term; Rip, 1992). Regimes can be changed when alternative solutions, developed in niches, reach critical mass, breaking the inertia of existing structures (Geels, 2004; Geels and Kemp, 2007; Geels and Schot, 2007; Lawhon and Murphy, 2012; Markard et al., 2020). Understanding these conditions can serve to accelerate the adoption of solutions, informing the design of processes that can deliberately promote the "transition" of socio-technical systems toward more collectively desirable equilibria, such as those that promote sustainable development (Shove and Walker, 2007).

The path toward transitions combines, therefore, two directions of change: (1) 'from below', innovation niches and 'experiments' that seek to innovate, generate learning, and show the possibilities of transitions are encouraged; (2) 'from above', transition 'agendas' are built and agreed upon, shared descriptions of the vision of the future to be reached and the trajectories to achieve them, which can positively predispose the system toward innovations generated in the niches (Voß et al., 2009), ideally built collaboratively among the key stakeholders.

This analytical lens may guide us to understand the specific factors that, in each territory, condition possible trajectories from conventional agriculture toward sustainable agroecological landscapes (Kleijn et al., 2019; Klerk et al., 2019). In this regard, previous studies indicate that the adoption of conservation agriculture practices, supported by public subsidies, often ends when economic incentives cease (Knowler and Bradshaw, 2007; Holden, 2018). In addition, farmer and farm household characteristics and management practices play a crucial role in the adoption of sustainable agricultural measures (Liu et al., 2018; Chatterjee and Acharya, 2021; Ruzzante et al., 2021). Likewise, preferences for sustainable agricultural practices may be influenced by farmers' knowledge, attitudes and beliefs, risk aversion, awareness of environmental and health risks, and valuation of ecosystem services, among other elements (Dessart et al., 2019; Elahi et al., 2021). Understanding the potential of SATs thus requires an integrative look at all these factors and how they can create opportunities for technological and institutional innovations allowing to scale up niches of agricultural innovation into larger transition processes in agri-food systems (Caron et al., 2014; Tittonell, 2014; Struik and Kuyper, 2017).

3.4 What are SATs for? Socio-technical imaginaries and observation frameworks on agri-food systems

While the previous approach helps understand what may push or hamper transitions, it does not necessarily tell us what (and who) these are for. In fact, this question is too often hidden away under the urgency of making the transition happen, which is in turn fueled by potent socio-technical 'imaginaries'. Imaginaries can be understood as deliberate attempts aimed at projecting a path to the future, often co-produced by the concerted action of various actors (Rip, 2012). While essentially illusory, imaginaries can be very productive in motivating action, equipping actors with a common anchor to try to influence the system and assemblages of which they are part toward, or away from; likewise, by presenting themselves as inevitable, they can function as self-fulfilling prophecies (Shove, 2010). Imaginaries also act as "boundary objects" to translate and articulate different perspectives and rationalities carried by key actors involved in such transitions (Urquiza et al., 2018). Governing transitions largely involves governing imaginaries. Conversely, studying imaginaries entails a work of discursive deconstruction highlighting the contingency of the perspective advanced by the imaginary to alternative agrifood paths and futures.

On the surface, it might seem that alternative production and consumption practices are mostly agreeing in a rejection of the agro-export model and emphasize food sovereignty, which refers to the right of peoples to determine their own ecologically and culturally appropriate way of eating, with an emphasis on local control and knowledge over agri-food systems. This right includes the resources necessary for food production, as well as access to land and water (La Via Campesina, 2021; Altieri, 1999; Altieri and Nicholls, 2009; Bacon and Cohen, 2013; Gliessman, 2013; Mastretta-Yanes et al., 2018). Likewise, they often emphasize returning to solidarity, collectivity, biodiversity, and care of seeds from the valuation of ancestral knowledge with local and territorial knowledge (La Via Campesina, 2018). However, looking deeper, it becomes clear that there is no 'one' imaginary on SATs, but rather, multiple alternatives often at odds with each other, which also depends on the specific trajectories of each transition context. Thus, understanding SATs and their potential also requires looking at territorially-embedded imaginaries on agri-food systems and their possible futures.

4 Case study: metropolitan region of Santiago, Chile

Hereafter, we illustrate the proposed approach and visualize its applicability through an exploratory analysis of the case of the Metropolitan Region of Santiago de Chile.

Chile is highly susceptible to climate change, meeting 7 of the 9 criteria used by the United Nations Framework Convention on Climate Change to identify high-priority territories. In the central areas of Chile, it is presented in a scenario of more than 10 years of 'mega drought' (Center for Climate Science and Resilience, 2015), with chronic precipitation deficits in the range of 25 to 45% (Garreaud et al., 2017) and possible future decreases of up to 90% in the flow of some rivers, in addition to a progressive reduction in Andean glaciers and in the levels of natural lakes and artificial reservoirs throughout the country (Center for Climate Science and Resilience, 2023). In addition, a significant increase in fires threatens vegetable and fruit crops, especially in the central regions of Chile (Ministry of Environment, 2021), while the growing frequency of heavy rains damages crops and reduces water infiltration and aquifer recharge (Fuentes et al., 2021).

The Metropolitan Region of Santiago (RM) is particularly interesting: the low snow cover in the area in 2021 makes the water landscape of the region critical (Center for Climate Science and Resilience, 2022), while the unprecedented economic and real estate boom it experienced in the last two decades (De Mattos, 2011; López-Morales et al., 2019), under a neoliberal economic model that commodifies natural resources, greatly increased pressure on water and soil supplies (Lukas and Fragkou, 2014). Agricultural soils in the region, in the face of the growth of Greater Santiago, have been depleted, concentrating activity in peri-urban areas (Zamora et al., 2012) while remaining ecosystems are fragile and threatened.

The Metropolitan region also has the highest concentration of population in the country, relying on a constant supply of fresh food, while vegetable production in the region corresponds to 32% of the national horticultural area (Instituto Nacional de Estadística (INE), 2023). This production is vulnerable to continuous climatic and anthropic pressures (Boza et al., 2019), compounding with the shortcomings of smallholder production, with poorly developed marketing channels, low use of management tools, high average age, limited access to technologies, and low adherence to associations.

The following sections offer a preliminary and exploratory analysis of the case from the lenses proposed above. Importantly, each section employs a different methodological approach and data sources to observe a different aspect of the case, combining more qualitative and quantitative research methods from different disciplines, informed by the conceptual lenses presented above. Importantly, these should not be understood as an exhaustive examination of the case but are only intended here at illustrating the observation framework and generating initial hypotheses about the territory under study (Table 1).

4.1 Risk, vulnerability, and agrifood resilience in the RM

To characterize the dimensions of sensitivity and resilience of the socio-technical food system of the territory, a review and analysis of scientific literature allowed us to identify key indicators for each dimension, as described below. Of course, this is a subset of all vulnerabilities and resilience factors, but they were found through literature on the study case to be the most relevant for the context, on top of being those on which secondary information could be gathered (Table 2).

Aggregate indicators of sensitivity and resilience were then generated, using weighted averages with equal weight. Finally, maps were generated to visualize communal differences. Considering the complexity of the food system, this analysis is limited to vegetable producers in the region, due to the availability of data and the already described importance of horticulture in the region.

The results are shown in the heat graphs (Figures 2, 3). In terms of sensitivity, the highest index corresponds to Melipilla and Paine, while the lowest values are present in Calera de Tango and Padre Hurtado. Examining the indicators in a disaggregated manner shows that among these communes, Melipilla has the highest *Water Footprint*, far above its peers. In addition, it also features high values in the *Scarcity Decrees* and *Water Stress* indicators. As for the commune of Paine, its sensitivity is due to high values in the indicators of *Land use capacity* and *Water source*, well above the rest of the sample. Conversely, the municipality of Calera de Tango features values in the *Water Footprint* and *Land Use Capacity* indicators well below the other communes, while Padre Hurtado presents low scores in all sensitivity indicators, with the exception of *Water Source*.

Regarding the resilience index, the highest values are found in the communes of Lampa, San Pedro, and Paine. While low values are found in the communes of Padre Hurtado, Pirque, and El Monte. When observing the indicators in a disaggregated manner, the municipality of Lampa features the highest values in the indicator *Surface area with technified irrigation,* and in the case of the communes of San Pedro and Paine, the indicator of *Surface area cultivated in greenhouses* stands out. Conversely, very low values in the indicator of *technified irrigated area* and *area cultivated in greenhouses* are observed in the communes of Padre Hurtado and Pirque.

4.2 Initial evidence on the resilience potential of agrifood practices in the RM: the cases of Melipilla and community gardens and orchards in the metropolitan region

As already indicated, the literature provides several examples of how agroecological systems are more resilient, have a greater capacity

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TABLE 1 Study cases and methodology.

Area of study	Methodology	Focus	Section
Rural areas of the Metropolitan Region	Quantitative approach. Indicators for sensitivity and resilience were identified by 61 paper reviews from WoS database, in the years 2014–2019. Keywords for searching were 'vulnerability', 'risk', 'territories', 'urban' and 'rural'. Research conducted in 2019.	Spatial characterization of the degree of risk and vulnerability of the region (Lens 1)	4.1
Organic organizations in Melipilla	Qualitative approach. 30 semi-structured interviews were conducted with farmers and experts. Research conducted in 2024.	Potential of agroecological transitions to generate resilience in the region (Lens 2)	4.2
Community gardens and orchards in the Metropolitan Region	Qualitative approach. 5 interviews with participants of urban farms, a survey applied to participants of urban farms, and participant observation of the 'bosquebarrio' project. Research conducted in 2024	Socioecological resilience in urban community gardens and orchard projects in the Metropolitan Region (Lens 2)	4.2
Metropolitan Region	Qualitative approach. 18 semi-structured interviews with alternative food networks farmers and experts (academia, policymakers, public institutions). Research conducted in 2023–2024	Opportunities, barriers and controversies associated with these transitions (Lens 3&4)	4.3

Source: own elaboration.

TABLE 2 Indicators used.

Risk dimension	Variable	Indicator	Source
Sensitivity	Water source	Percentage of cropland area with surface water sources	Vegetable Cadastre 2022
	Recurrence of shortage decrees	Recurrence of declaration of water scarcity decrees by the DGA	ARCLIM
	Over-granting of water rights	Over-granting of water exploitation rights	ARCLIM
	Basal water stress	Estimated basal water stress globally	ARCLIM
	Land use capacity	Communal area whose land use capacity includes V, VI, VII and VIII.	CIREN 2015
	Water Footprint	Total water footprint of the municipality by productive and sanitary uses.	ARCLIM
Resilience	Irrigation technology	Surface area of vegetables with irrigation technology	Vegetable Cadastre 2021
	Greenhouse use	Surface area of vegetables grown in greenhouses	Vegetable Cadastre 2021

Source: own elaboration.

to recover from disturbances, particularly extreme weather events such as drought, floods, or hurricanes, and can resist attack by pests and diseases (Food and Agriculture Organization of the United Nations (FAO), n.d.). However, in Chile at least, few studies are available specifically examining how this potential manifest itself and/or what factors may facilitate or hinder its realization. Here we present two exploratory studies employing the resilience approach proposed in 3.2 to understand how the agroecological approach can lead to resilience in urban gardens and orchards in the RM.

4.2.1 Organization of organic producers of Melipilla

In the commune of Melipilla, connections and ties have been established within the farmers, coming to create the group called 'Organization of Organic Producers of Melipilla' or OPOMEL, where organic and agroecological farmers are found, which seek clean production, conserving, protecting, and regenerating the environment, adapting to changing climate conditions. OPOMEL is the first organization of organic producers in the commune of Melipilla and the second in the province, since July 2019, as they are certified by the Agricultural and Livestock Service (SAG).

For this research, 15 farmers were interviewed, together with 15 experts. While farmers in the commune usually display high diversification and rotation of crops, including both fruit and vegetables. Among the interviewers, the most predominant cultivation was tomato, of which different varieties were grown, both for sale and for re-plantation. Some of this was done on open air and some through greenhouses.

According to the informants, agroecological practices allow more diversity in terms of species and varieties, as well as in spatiality and temporality of the cultures. The interviewees are in a constant search for innovation in their production processes, striving to improve and adapt to the new realities of the agricultural sector due to climate change.

Agroecological principles were often mentioned for the design of biodiverse, flexible, energy-efficient, and resource-conserving agricultural systems, which include increasing biomass recycling and providing favorable soil conditions by managing organic matter and improving soil biological activity (Altieri and Nicholls, 2012). Within this approach, farmers mostly manage the soil resource through the incorporation of organic matter such as cow, chicken, or horse guano, obtaining it through the animals they have or thanks to livestock from surrounding neighbors. The incorporation of organic matter improves soil structure, increasing moisture retention, better structuring of mineral particles, greater aeration, and less mechanical impedance to root growth (Sierra and Rojas, 2003).

4.2.2 Community gardens and orchards in the metropolitan region

The management of orchards and gardens is a source of resilience for ecosystem services (Colding et al., 2006), for communities, and for individuals (Okvat and Zautra, 2011), hence the motivation to analyze

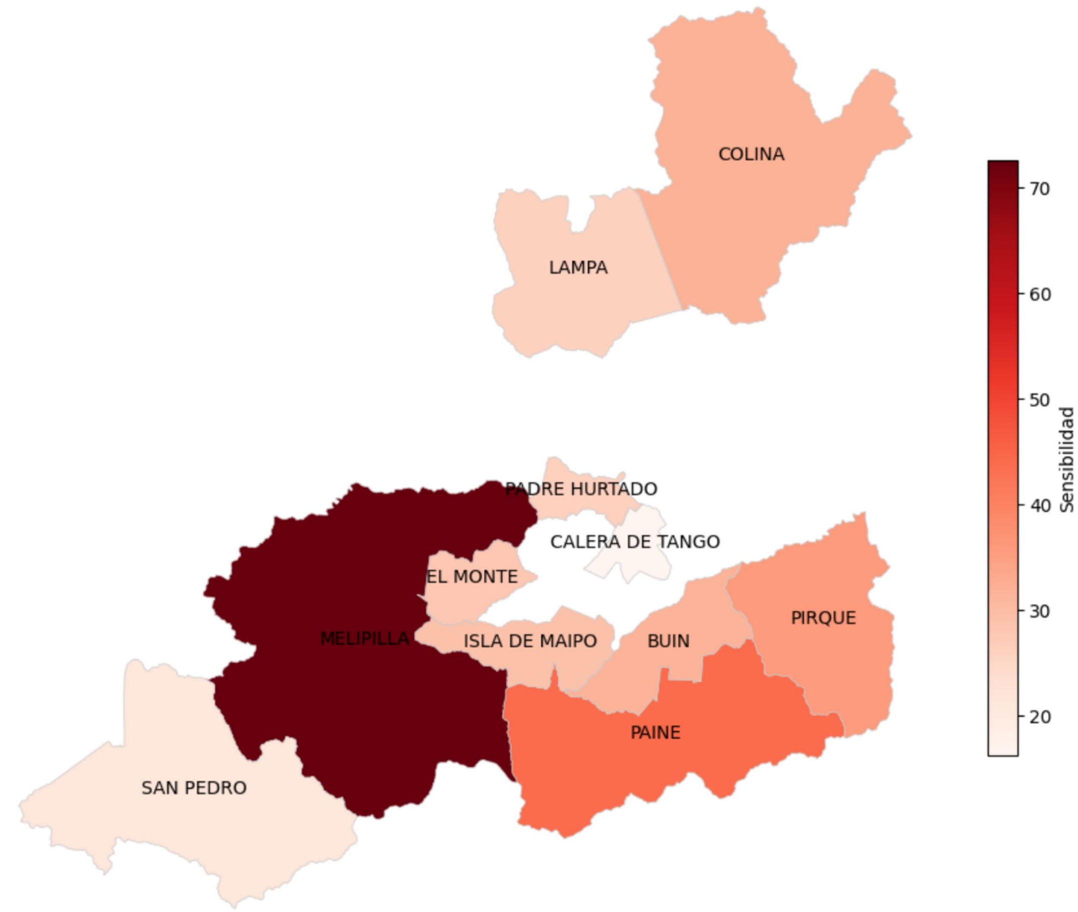

FIGURE 2
Sensitivity map by commune. Source: own elaboration.

the resilience of the operation and maintenance at the level of the orchard-garden and the collective that sustains it, understanding that this is the operational level of its strategy. This approach sought to characterize these initiatives seen as socioecological systems and to elucidate their limits in the context in which they operate. For this purpose, an autoethnographic research was carried out to investigate how socioecological resilience is expressed in transition initiatives, specifically in urban community gardens and orchard projects in the Metropolitan Region. The project studied was 'Bosquebarrio' in La Florida. Interviews were also conducted with gardeners, leaders, and members of organized initiatives in the region.

It was found that the most recent urban orchard and community garden initiatives stand out for being much more diverse, specifically in terms of the botanical composition chosen. This is the result of the incorporation of new practices and plant associations that seek to adapt to local climatic conditions, facilitate their maintenance, and provide greater diversity of ecosystemic and food contributions. These new approaches expand the boundaries of what is traditionally considered an orchard or garden, blurring the distinction between the two, and claiming other principles such as 'ecosocial regeneration'.

A clear example of this is the so-called 'edible forests' that incorporate elements of landscaping, permaculture, and agroecology. And more recently, approaches such as syntropic agriculture, which have come to revolutionize the limits around incorporated biodiversity, planting density, and associations of medicinal, fruit, and native species. This is a very broad field of study full of nuances that academia has not yet been able to assimilate, while grassroots organizations are daring to experiment by adapting these principles to their contexts.

4.3 Gaps, opportunities, and imaginaries of transitions: challenges and opportunities for the SATs in the RM and the role of public policy

Although the concept of 'agroecological transition' is relatively young in Chile, the discourses on sustainability, ecology, and agroecology have accompanied the development of urban gardens and orchards since their origin, being part of the justification for their existence. Thus, it is interesting to analyze how socioecological resilience is perceived and expressed in these initiatives that precisely seek to be a channel for environmental education and the implementation of an ecological paradigm. Applying the framework of socio-technical transitions and imaginaries, this section presents the results of qualitative research on discourses and imaginaries of SATs.

It is important to note that the current executive, in the framework of its plan for a just water transition, has proposed to promote the

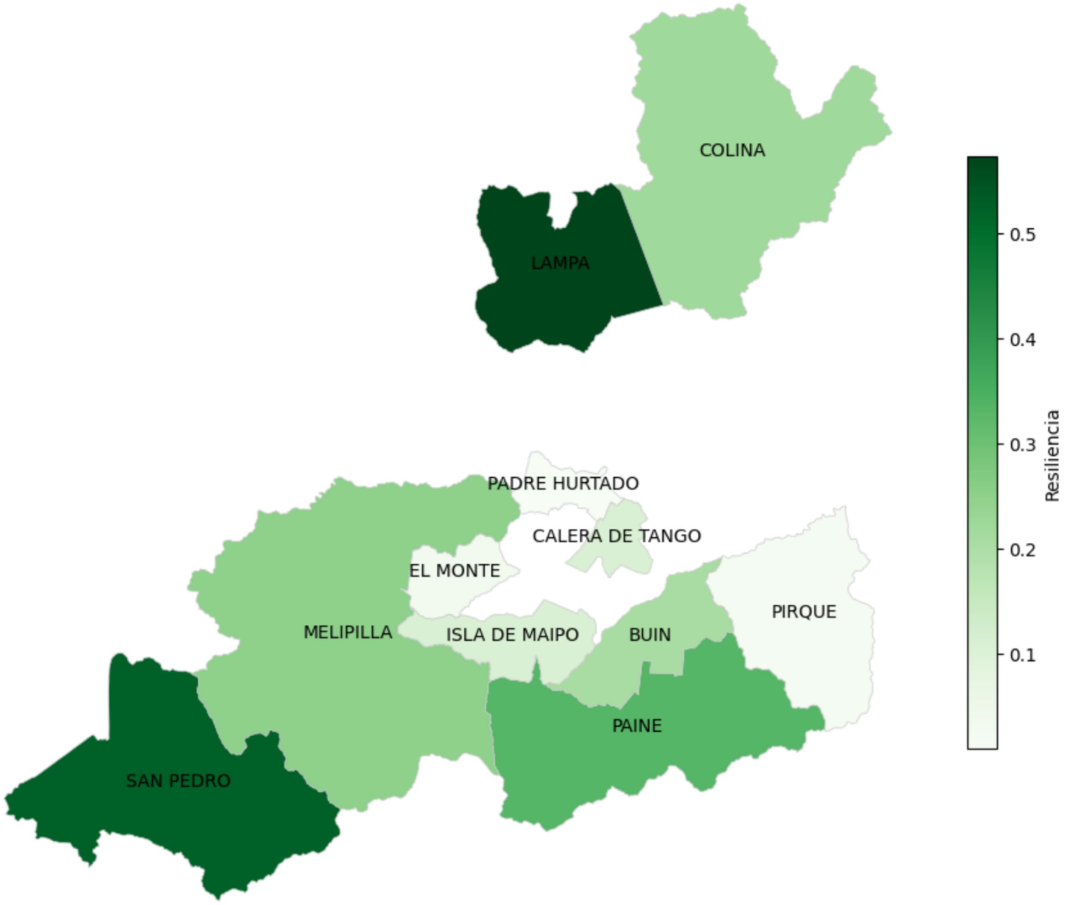

FIGURE 3
Resilience map by commune. Source: own elaboration.

development of agroecology to promote food security and sovereignty in the country. This, at the same time, responds to the context of the megadrought that has been haunting the country for more than a decade and that is expected to continue or increase under current climate projections and in consideration of current patterns of land and water use (Center for Climate Science and Resilience, 2023).

However, until now it has remained unclear how these political and scientific imaginaries connected (or disconnected) to those of other key actors, thus the preliminary results presented here shed some new light on these issues.

4.3.1 Gaps and transition opportunities

The discourses identify certain gaps that limit the scaling up of ecological 'initiatives' and that have a structural origin that determines the possibilities of change in the food system. The food system, understood as all those activities and interactions that occur in production, distribution, and consumption of food, is seen as a system controlled by agribusiness, a sector that concentrates commercial power and access and management of productive resources (land and water) and operates under a logic of profit maximization:

> *"Santiago de Chile has a legal vacuum that is sustained in a mixture between a free market and an informal market, where the system works; it manages to bring food to the houses in a more or less cheap way, but there are some powerful gaps in regulation and asymmetry of negotiation. And those that somehow end up reproducing inequalities in almost every aspect of life".* (Academic).

This is directly related to international treaties that delimit the margin of possible transformations, since any change at the public policy level is subject to the international food treaties that delimit the margins of action.

In this sense, Chile looks to be still lacking in food policies: "*the food system in the country, being a country as rich as we are in biodiversity and land suitable for agriculture, we are very poor in food policies, too poor*" (Farmer). In the current context, there are at least three baseline public policies to talk about food systems; the first is the National Food and Nutrition Policy (2018), followed by the National Sovereignty Strategy for Food Security (2023), and the Transition to Sustainable Agriculture Program (2023–2024).

Although informants denote progress in this area, there are still no concrete actions that directly support Peasant Family Farming (AFC) or other types of initiatives, especially in the economic sphere: *"There are initiatives, but they are just that; they are local initiatives (...) my feeling is that there is no public policy behind these good practices that would allow them to be sustainable"* (Academic). In this sense, they are still insufficient compared to policies that promote large-scale and export production.

On the other hand, according to the niche experiences of "other" women farmers known to the interviews, these are difficult to scale, especially if one wants to supply a population such as that of Santiago. In productive terms, these experiences do not meet the demand for fresh food and would require the work of more people, which is an economic gap for small gardens.

> *"A1: of course, to have one hectare worked like that, you need a lot more people to reach that; to have that production as optimal in such a large piece of land, it is not scalable; it is impossible.*
>
> *A2: the model could be scaled up, but not to human scale"* (bio-intensive farmers in RM).

Here another relevant problem emerges: the insufficiency of available land for work by the AFC, access to land being one of the main difficulties currently faced by farmers:

> *"The main difficulty (…) is to get a piece of land (…) Here in Chile, buying a piece of land is very expensive, so there are these limitations (…). This has no possibility of becoming widespread for now as long as the land is not distributed"* (self-supplying farmer in RM).

In this sense, there are structural aspects that must change for a transition to occur toward a system that can supply a large population. Despite all these difficulties, some stakeholders say that the fact that there is a strategy and that the concept of sovereignty is being discussed is already a step forward: *"the word sovereignty was not a word that existed in Chile (…) So when this strategy and the speech of a minister talking about food sovereignty appeared, it was very encouraging; it opened these dialogues"* (academic).

Finally, a visible process of de-peasantization is ongoing, since working the land implies a high sacrifice and is little valued, which has led a large number of young people to migrate from the countryside to the city, the sale of land to large industries, loss of traditions, among others. The AFC is constantly impoverished due to the price control of intermediaries, who take most of the profits. Thus, the supply centers in the region have prices set by middlemen and not by those who produce food:

> *"…how absurd that the person who is going to consume my pumpkin, which we have paid for and sell at a fair price, has to earn more than us who work our asses off in the fields producing it"* (Biodynamic farmer).

Despite this, there is a 'folkloric' notion of the countryside, a romantic idea of agriculture as tradition and linked to heritage, where visiting local farmers' markets would be a 'cultural' activity, and they fail to establish themselves as an established distribution system that can compete with traditional sales and purchasing chains.

4.3.2 Imagining futures: moving toward "other" systems

When talking about the future of SATs in the region, the first thing that comes to mind is the imaginary installation of local markets:

> *"The ideal is based on two concepts. In local trade and in the regeneration of soils. I believe that these are two concepts that should be in food production and in this national food network (…). Throughout Chile, people should be able to access this type of food through a garden near their home or even in their community, 10 km away"* (Bio-intensive farmer in RM).

There is consensus that the appropriate way to produce food should be ecological, and the current political strategy has this focus; however, what still needs to be strengthened and what is more important in the imagination is the local supply, in urban and rural areas of the region, having greater sovereignty over food:

> *"For people who live in the city, they should also start to look for these community gardens, (…) and they could also choose what we eat, like having a little more right to have a variety of things (…); here in the more rural areas, every so often, have polycultures, have market gardens to feed the community (…), so people will buy from the local farmer…"* (Agroecological farmer in RM).

However, there are differences in the accounts on how these local markets should work. Some consider that local commercialization should arise from the farmers' own organization, that these should be constituted as microenterprises and, in this way, local markets should be developed. Others, however, think favoring more direct commercialization channels from farmers to decentralized consumers, stressing the increased autonomy and adaptability to the possibilities of each farmer. In both cases, the State support is considered essential for the sustainability of these markets and the affirmation of farmers in the local markets, with fair prices for them and for consumers:

> *"Traditional agriculture has sufficient incentives to function, and for some reason it is also doing so; the market endorses it, and so it also pays for it, so there is a lack of initiative for this to happen, but in sustainable and more agroecological family farming"* (Transition program advisor).

In this sense, in the future imaginary of SATs, the State plays an active role in the incentive and promotion of "other" agriculture and marketing channels, as well as in raising awareness among the population about food consumption.

Along the same lines, organic certification is discussed by the interviewees as one of the ways to strengthen the local market. In this regard, two perspectives are identified. There is a critical view that the certification process makes products more expensive and is oriented toward large-scale production, linked to large companies, while on the other hand there is the view that certification can be a good way to promote these forms of organic production, giving them an 'added value' and that in this way many farmers could enter the market by having a distinctive seal.

Finally, SATs are associated with a greater organization on the part of farmers and with a more communitarian logic in the relationships involved in rural and/or urban gardens. This would imply establishing major changes in the relationships between agents, *"it is a change of paradigm, of culture"* (self-sufficiency farmer in RM), and not only for farmers, but for all the actors involved: public and private, academia, social organizations, and others who should be articulated to be able to carry out a joint project.

5 Final considerations

Based on the above, it is possible to conclude that the conceptual frameworks for the case studies allow a profound and multifaceted inquiry on different fronts of the potential of SATs for climate adaptation.

The risk lens and its operationalization in indicators and maps of sensitivity and resilience reveal an unequal distribution of risks and adaptive capacities. Communes such as Melipilla and Paine, despite their high sensitivity, also stand out positively in some aspects of resilience, reflecting part of the complexity of these territories. This resulting heterogeneity makes it possible to identify key factors when designing public policies that are relevant to reduce sensitivity in the most vulnerable areas and strengthening resilience in those with lower adaptive capacity.

The resilience framework in the cases of community gardens highlights and exposes those key components and practices related to the diversity, memory, and transformation of the initiatives, contributing directly to favoring their socioecological memory by systematizing their activities over time and their importance for their different functions and purposes.

On the other hand, the approaches of transitions and socio-technical imaginaries allow understanding the hindering and facilitating factors for the scaling and massification of these solutions beyond the innovation niches where they are often developed, making it possible to evaluate both the practical feasibility of the SATs, which according to the accounts, require social, economic, and political structural transformations to be able to put a SATs on track according to the imagined futures.

In conclusion, while these are only preliminary results, there seems to exist a need for adaptation, and, at least on paper, SATs seems to be well-suited to answer it. However, the question about the scalability of these SATs, considering the existing regime, remains open, and the co-existence of multiple and partially contrasting imaginaries on the destinataries of the benefits and their appropriability by those who most need them -the most vulnerable farmers and the population's food security- stands unclear. This brings doubts on the real potential of SATs as an adaptation strategy as it stands, while it also points to aspects that may be targeted to improve these strategies. For instance, it highlights the need of more open debate and discussion on what a SATs means, which SATs will be prioritized, and how local communities and farmers can be expected to be part of it; and also, a better analysis of the socio-economic and governance regime, which may hamper and/or drive the feasibility and scalability of SATs beyond the niche level.

Agriculture is not only a productive-economic sector but also a driver of the food environment, a way of life anchored with particular cultural and historical aspects (Lytle, 2009). In this sense, adopting a holistic and systemic view of food security and the different elements that can generate risks to it, or promote its resilience, from a systemic and territorial approach, allow us to understand why SATs are necessary and how they can become potential strategies to promote food security in a context of climate change, or oppositely, how they can fall prey to different kinds of biases, limitations, and challenges that may significantly hamper their adaptation potential.

The proposed approach addresses it in its complexity, highlighting the multiple interconnections between natural, technical, and social elements that would tend to remain invisible in traditional management strategies and that could lead to ineffective or even counterproductive adaptation strategies for the system (Marschke and Berkes, 2006; Holling and Meffet, 1996).

From this perspective, thinking the transformation of agrifood systems toward sustainability must be part of a change in the socioeconomic, political, and ecological relations that are currently permeating the agrifood system and that place small-scale producers with ecological production practices at the center of public policy (Alonso-Fradejas et al., 2020). This connects with emerging views about transformation to sustainability, which require combining more system- and structural-level approaches with others deriving from the bottom-up work with local communities (Billi et al., 2022; Juri et al., 2022; Juri et al., 2024) and require considering how the framings of this transition depict the roles and the winners and losers in the process of transition (Huntjens and Huntjens, 2021; Fiala et al., 2024).

The case study, as well as the operationalization of the lenses presented through the decision-tree and the theoretical discussion, allows us to visualize the potential of this tool for a more comprehensive and holistic understanding of the real potential of strategies such as those described to promote adaptation to climate change, as well as to visualize possible gaps or maladaptive effects and potential ways forward.

A significant limitation of this study is that the data that we used for risk and vulnerability analysis are point-in-time and not time series. There are no available time series at the moment for this kind of information, and in fact, quantitative data is also limited, which is part of the reason we decided to resort to qualitative interviews instead. However, in the future we are planning to complement this with primary sampling of information, which is, however, outside the scope of this preliminary study.

Importantly, our work is not meant to advocate for one specific methodology but rather for the need and possibility of a more integrated, systemic understanding of the different conditions needed for the assessment of the adaptation potential of sustainable agrifood transitions, acting thus as an interdisciplinary conceptual outlook to combine different strands of literature on the topic. In this sense, each of the analytical components can be, in fact, achieved through different methodological approaches, both qualitative and quantitative.

In the future, it will be necessary to develop more exhaustive and complete applications of the methodology in real cases to further refine the lenses and generate useful knowledge to fully understand these strategies, something that becomes urgent and essential in view of the growing relevance that these are having both in public policy and in private voluntary actions, both in Chile and in the Latin American region as well as in the world.

Data availability statement

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding authors.

Ethics statement

Written informed consent was obtained from the individual(s) for the publication of any potentially identifiable images or data included in this article.

Author contributions

MB: Conceptualization, Supervision, Writing – original draft, Writing – review & editing, Validation. VB: Conceptualization, Investigation, Writing – original draft, Writing – review & editing, Supervision. JN: Conceptualization, Investigation, Writing – original draft, Writing – review & editing. CJ: Investigation, Writing – review & editing. RC: Investigation, Writing – review & editing. SP: Investigation, Writing – review & editing.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Generative AI statement

The author(s) declare that no Gen AI was used in the creation of this manuscript.

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