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Power, Governance and Resilience in a Chilean Fruit Agro-Export Value Chain: A Social Simulation Approach

Oswaldo Terán ^{1,2,*}, Karla Soria-Barreto ¹ and Cristian Morales ¹

¹ Escuela de Ciencias Empresariales, Universidad Católica del Norte, Coquimbo 1780000, Chile; ksoria@ucn.cl (K.S.-B.); cmorales@ucn.cl (C.M.)

² Centro de Simulación y Modelos (CESIMO), Facultad de Ingeniería, Universidad de Los Andes, Mérida 5101, Venezuela

* Correspondence: oswaldo.teran@ucn.cl

Abstract

The fruit agro-export value chain in northern Chile faces governance and water-related challenges that affect its resilience and long-term sustainability. In the context of sustainable agriculture, these challenges highlight the need for integrated approaches to understand how socio-economic and environmental factors interact. This paper proposes a set of measures to assess resilience using a social simulation model based on the Sociology of Organized Action, implemented through the Social Laboratory (SocLab) platform. The model represents actors, their resources, and their interactions as a system driven by strategic behavior. The proposed measures are applied to analyze both simulation outcomes and the structure of the model. The findings indicate that resilience is constrained by power imbalances among actors and by external pressures related to water scarcity. In particular, simulation results show that the influence of Producers reaches only approximately half that of the Public Sector, revealing a significant power imbalance within the value chain. These imbalances create vulnerabilities that limit the system's capacity to absorb disturbances and adapt to environmental stressors, which are expected to intensify due to climate change and increasing demand. In addition, the resource associated with coordinating actors around the efficient use of water exhibited the highest relevance among the resources considered, highlighting the central role of water governance in shaping resilience. The study contributes by integrating a simulation-based approach with economic and institutional perspectives, linking the distribution of influence among actors to value allocation along the chain, as conceptualized in marketing margin analysis, and interpreting governance structures through Transaction Cost Economics. This integration provides a more comprehensive understanding of how power distribution, coordination mechanisms, and transaction costs jointly shape resilience and sustainability in agri-food value chains.

Keywords: agri-food value chains; resilience; governance; sustainable agriculture; social simulation; transaction cost economics; value distribution

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1. Introduction

The food system faces challenges such as climate change, extreme weather events, and environmental degradation (FAO, 2023) [1], requiring a shift in perspective towards a global food value chain (GFVC) [2,3]. A GFVC integrates value-creating activities from

raw materials to final products, emphasizing quality, information sharing, and interdependence among actors [4,5]. Governance and resilience are critical for GFVC success and are increasingly recognized as key dimensions of sustainable agricultural systems [6,7]. While governance facilitates market orientation, resilience ensures stability, particularly in developing countries reliant on the agri-food sector [8]. However, studies on agricultural value chain resilience remain limited [9]. In this context, new approaches to resilience, such as simulation models, and innovative methods of measuring resilience, like those offered in this paper, are highly relevant. In this sense, strengthening resilience in agri-food value chains is a key component of advancing sustainability transitions in agricultural systems.

Chile's agri-food sector contributes 18% to GDP and employs over 1.2 million people [10,11]. The Coquimbo Region, with 3.4% of national agricultural land, is a major producer of pisco grapes and fresh fruit, exporting 95.5% of its agricultural products [12]. However, reliance on rainfed agriculture (50.4% of land) increases vulnerability to climate change, underscoring the need for effective governance and resilience strategies. These challenges highlight the importance of developing sustainable agriculture strategies that integrate governance, resource management, and adaptive capacity. The region's agricultural structure is polarized, with small farms (<20 ha) covering only 0.2% of the exploited land, while large farms (>100 ha) dominate production [11].

Although the empirical application focuses on the Coquimbo region, similar challenges can be found in other agricultural regions characterized by water scarcity, climate variability, and complex governance arrangements, such as California in the United States, southeastern Spain, coastal Peru, and parts of Australia. Therefore, the analytical framework proposed here may also be relevant for understanding resilience and governance in other water-constrained agri-food systems.

This study suggests measures of resilience and applies them to assess governance and resilience in the fruit agro-export value chain in the Coquimbo region using the Social Laboratory (SocLab) simulation platform (SocLab-2016-10-14 release) (for related studies see, e.g., [13,14]), based on Crozier & Friedberg's [15] theory of organized action. Afterwards, the paper suggests action strategies to enhance resilience.

Few studies have explored social simulation for power management in resilience enhancement or proposed resilience measures based on simulation outputs, though interest is growing [15,16]. Jensen et al. [16] propose a method for preparing for future crises and enhancing resilience based on prior experiences with social simulations. Furthermore, Alf et al. [17] have conducted a comparative analysis of simulation games focusing on sustainability and business scenarios. In this line of research, a workshop on Agent-Based Simulations for Societal Resilience in Crisis Situations took place at the Lorentz Center (Leiden) from 27 February to 3 March 2023 (<https://www.lorentzcenter.nl/agent-based-simulations-for-societal-resilience-in-crisis-situations.html>, accessed on 10 March 2026).

This study contributes to the literature by integrating a simulation-based approach grounded in the Sociology of Organized Action with complementary economic and institutional perspectives. Specifically, it links the distribution of influence among actors obtained through the SocLab model with the allocation of value along the chain, as conceptualized in marketing margin analysis, while governance structures are interpreted through the lens of Transaction Cost Economics. This integration provides a more comprehensive explanation of how power asymmetries, coordination mechanisms, and transaction costs jointly shape value distribution and influence the resilience and sustainability of agri-food value chains.

The novelty of this study is threefold. First, it proposes resilience indicators derived from the structure and outputs of a social simulation model grounded in the Sociology of Organized Action. Second, it applies these indicators to an agri-food value chain affected

by water scarcity and governance challenges. Third, it integrates social simulation with complementary economic and institutional perspectives, linking influence structures to value distribution and governance arrangements. This combination provides an analytical framework capable of jointly examining resilience, governance, coordination processes, and value allocation in agri-food. The article proceeds with a conceptual framework, methodology, simulation model, results and discussion, and conclusions.

2. Theoretical Framework

This section develops the theoretical framework of the study, linking governance and resilience in agri-food value chains with economic and institutional perspectives, including marketing margin analysis and Transaction Cost Economics.

2.1. Marketing Margin Analysis

Marketing margin analysis examines how value is distributed across the stages of agri-food value chains through price differences between farm-gate and final markets [18]. Although these margins partly reflect processing and logistics costs, they are also shaped by structural factors such as market power and bargaining asymmetries [19,20].

From this perspective, marketing margins can be interpreted as an observable outcome of underlying power relations. Actors with stronger coordination capacity or market access tend to capture a larger share of value, whereas primary producers often face more limited margins. In this study, this distribution is linked to the configuration of influence among actors in the simulation model, allowing margins to be interpreted as an economic expression of simulated power structures.

2.2. Institutional Economic Theory

Institutional Economic Theory, particularly Transaction Cost Economics (TCE), provides a framework to explain governance structures in agri-food value chains. TCE suggests that actors select governance arrangements—such as markets, contracts, or relational coordination—based on their capacity to minimize transaction costs associated with uncertainty, asset specificity, and repeated interactions [21,22].

In agricultural contexts, these conditions often lead to hybrid governance forms, including contracts and coordinated relationships [23]. Informal mechanisms such as trust and reputation also play a key role in reducing transaction costs [24]. In this paper, these elements are interpreted through the interaction structure of the model, where patterns of dependency and coordination reflect different governance arrangements and their associated costs.

2.3. Governance

Governance is crucial in determining actor participation in the global value chain (GVC) and shaping negotiation conditions [25,26]. It can be understood as the set of mechanisms that coordinate actors and sustain cooperation to achieve collective objectives [21,23,27]. Key governance elements include lead actors, shared governance, information exchange, and network facilitation [28], which enhance market orientation and sustainability amid challenges like climate change [3,29].

GVC governance takes five forms—hierarchical, captive, relational, modular, and market-driven—varying in coordination and power asymmetry [3]. Network governance can be highly mediated, with a single leader, or sparsely mediated, with decentralized interactions [30]. The food sector has extensively studied agri-food value chains, emphasizing governance for socio-organizational improvements [31].

Globalization, technology, ownership concentration, and climate change have transformed GVC governance [26]. Both formal (contracts) and informal (trust, commitment)

relationships shape governance and market orientation [27,28]. Trust and commitment foster information exchange, supporting sustainable value chain governance [32,33]. Theoretical models highlight leadership, shared governance, and facilitation as key governance aspects [31].

2.4. Resilience of the Value Chain

According to González et al. [34], resilience in systems involves buffering (maintaining control), self-organization (self-management), and learning/adaptation [35,36]. Resilience is increasingly understood not only as the ability to resist disturbances but also as the capacity to adapt and reorganize in response to change [6]. Similarly, recent frameworks on agricultural resilience distinguish between absorptive, adaptive, and transformative capacities [6,7]. Absorptive capacity refers to the ability of a system to maintain its functions under disturbances; adaptive capacity concerns adjustments in response to changing conditions; and transformative capacity involves more fundamental changes in governance, institutions, or resource management when existing structures become unsustainable. Resilience is therefore best understood as a dynamic and adaptive process rather than a fixed state [37]. Collaboration, learning, and empowerment contribute to resilience, which depends on resources, knowledge, and management capacity [38,1].

Vroegindewey and Hodbod [4] define resilience as a system's ability to maintain services despite disruptions. In agri-food value chains, resilience governance involves two layers: i) interacting resources (e.g., processors, traders), and ii) institutions that manage and coordinate these resources. Governance therefore plays a central role not only in maintaining system performance under disturbances but also in facilitating adaptation and, when necessary, transformation in response to long-term challenges such as climate change, water scarcity, market concentration, conflicts, and rising costs [1]. Resilience is consequently a key dimension supporting the social, environmental, and economic pillars of sustainability [39].

Maintaining resilience requires addressing external (e.g., economic, climate, geopolitical) and internal (e.g., degradation, tipping points) disturbances. Agri-food value chains face disruptions from droughts, infrastructure gaps, and fluctuating policies. Strategies to enhance resilience include improved coordination, power balance, and incentives for collaboration. Governance elements like bargaining power, contracts, and market influence shape resilience [40].

In developing countries, resilience in agri-food value chains is vital for employment, income, and food security [4,41]. However, studies on resilience, and consequently on measures of resilience, in these contexts remain scarce [9]. Crozier & Friedberg's [15] theory of organized action suggests actors strategically adjust behavior within a social game, influencing power dynamics and resource exchange. This balance of power and actor satisfaction serves as an indicator of resilience.

This study examines relationships within the agro-export sector, focusing on key actors in the global value chain (GVC): producers, exporters ([42], first level), as well as water management officials, and the public sector ([42], second level). It employs resilience measures based on simulation outputs and the model's structure to analyze these dynamics.

3. Methodology

This section presents the methodological approach adopted in the study, based on the Sociology of Organized Action and implemented through the SocLab simulation framework. It describes the methodological process followed in the paper; modeling of actors, resources, and interactions; the definition of resilience measures derived from the model's structure and simulation outputs; and an interpretation from the integration of

economic and institutional perspectives through marketing margin analysis and Transaction Cost Economics.

3.1. Overview of the Methodological Process

To facilitate the understanding of the methodological procedure followed in this study, Figure 1 summarizes the main stages involved in model construction, validation, simulation, and resilience assessment. The procedure begins with the elicitation of expert knowledge through interviews, followed by the identification of actors, resources, solidarities, stakes, and effect functions needed to construct the SocLab model. The resulting model is subsequently validated by experts and then used to conduct simulation experiments and structural analysis. Resilience is assessed through three indicators—power balance, satisfaction balance, and resource relevance—and the results are interpreted through marketing margin analysis and Transaction Cost Economics to evaluate governance and resilience within the value chain.

As shown in Figure 1, resilience assessment is based on a sequential process that combines expert knowledge elicitation, formal modelling through the SocLab framework, simulation experiments, structural analysis, and the interpretation of results from economic and institutional perspectives.

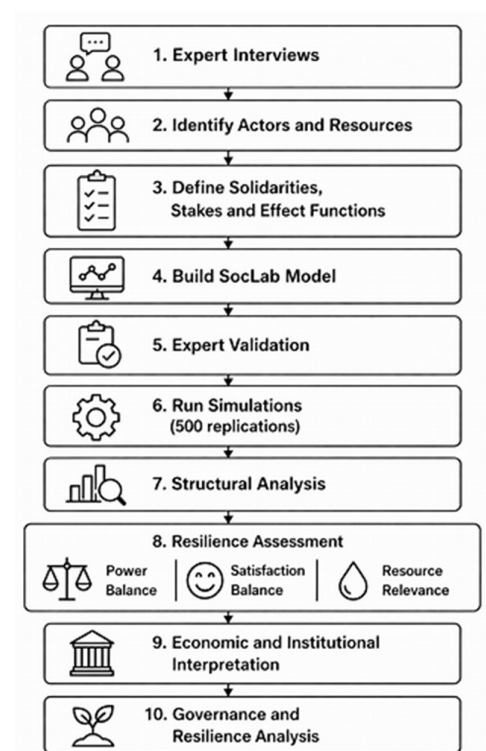


Figure 1. Methodological framework of the study based on the SocLab model.

3.2. Modeling the System: Systems of Organized Action and SocLab

The SocLab framework [43–46] formalizes the *Sociology of Organized Action* (SOC) of Crozier and Friedberg [15]. SOC analyzes how organizations stabilize through counterbalancing processes of power between actors, as in community interactions or agricultural systems. Power arises from actors' control over resources needed by others. Since actors have bounded rationality and act in complex environments [47], their behavior is strategic, aiming to balance organizational roles with personal goals. A social game ends in a stationary state when all actors' satisfaction exceeds their aspiration.

The formalization implemented in the SocLab platform [48] makes it possible to represent the structure of an organization as an instance of a generic meta-model. This representation allows researchers to analyze structural properties using analytical tools, investigate the range of possible organizational configurations (thereby identifying Pareto optima, Nash equilibria, structural conflicts, among others), and simulate the outcomes of social interactions to estimate how actors are likely to behave toward one another within a given organizational setting.

To achieve its goals within a social system, each actor needs, and thus depends on, resources managed by others. The management of a resource determines how it can be used by others so that it is the base of a relation between the manager and the users of the resource. The dependency of an actor on a resource is expressed by its stake and an effect function. The stake of an actor on a resource expresses how much it depends on this resource, on a scale null = 0, negligible = 1,..., significant = 5,..., critical = 10. Each actor has 10 stake points to distribute on the set of all resources.

The effect function associated with a resource and an actor indicates the extent to which the management of that resource by its controller either facilitates or hinders the actor's ability to achieve its objectives. The x -axis represents the state of the resource, that is, the manner in which it is managed, ranging from the least cooperative (negative direction) to the most cooperative (positive direction) with respect to all actors. The y -axis represents the actor's capability to attain its goals as a consequence of that management.

The impact of a resource r having the management m upon an actor a , i.e., the capability it provides to this actor to achieve its goals, is the value of the $\text{effect}_{r,a}(m_r)$ function applied to m , weighted by the stake of a on r . As a result, an actor gets some satisfaction, as an aggregation of the impacts it receives from the resources it depends on, and, conversely, it exerts some influence, as an aggregation of capabilities it grants to actors who depend on the resources it controls. When a system of organized action is in a configuration $m = (mr)r$, the capability got by an actor a is defined as:

$$\text{capability}(a, m) = \sum_{r \in R} \text{stake}(a, r) \times \text{effect}_{r,a}(m_r). \quad (1)$$

From this, we can define the satisfaction of a as (calling A the set of all actors):

$$\text{satisfaction}(a, m) = \sum_{b \in A} \text{solidarity}(a, b) \times \text{capability}(b, m) \quad (2)$$

Conversely, the influence exerted by actor a over actor b is defined as the sum of the capabilities it supplies to the actors, towards which b has solidarity by the management of the resource(s) it controls, that is:

$$\text{influence}(a, b, m) = \sum_{c \in A} \text{solidarity}(b, c) \times \text{capability}(a, c, m) \quad (3)$$

Finally, the influence of a is the sum of the influence of a on all actors:

$$\text{influence}(a, m) = \sum_{b \in A} \text{influence}(a, b, m) \quad (4)$$

The decision-making mechanism of SocLab actors is described in [45,49]. Within this framework, actors attempt to maximize their satisfaction while operating under conditions of bounded rationality. Each actor possesses an aspiration variable that is initially set to the maximum attainable satisfaction and progressively adjusts toward the actor's current level of satisfaction according to a reality principle. The greater the discrepancy between aspiration and current satisfaction, the more actively the actor explores its environment, making substantial modifications to the management of the resources it controls. When all actors achieve a level of satisfaction that exceeds their aspiration, the system reaches a stationary state and the interaction process terminates. This situation is interpreted as a regularized state in which every actor perceives that it has attained the highest feasible level of satisfaction for pursuing its objectives.

3.3. Measures of Resilience: Power, Satisfaction and Resource Relevance

Equity or fairness and participation are two central elements of resilience, as discussed earlier. Therefore, potential outputs that can be used as measures of resilience in SocLab include global balances of: (i) power (influence), (ii) satisfaction, and (iii) relevance of a resource. Imbalances signify that an actor is in a better condition than others, potentially leading to inequality and weakness in the system. Furthermore, the fairness provided by a well-balanced system supports resilience principles (as proposed by Vroegindewey and Hodbod [4]), such as: (i) enhancing the potential for stakeholder participation, information gathering, and learning about the systems, and (ii) promoting polycentric governance. Additionally, the favorable state of critical resources, such as water management in the case of our model, related to fruit production, provides insights into the resilience of the system. All these potential resilience indicators are interconnected with the structural and dynamic configuration of the model. From the perspective of resilience theory, balances of power, satisfaction, and resource relevance provide information about the capacity of the system to maintain its functioning under disturbances and to adapt to changing conditions. In this sense, the proposed indicators are particularly related to the absorptive and adaptive dimensions of resilience discussed by Béné et al. and Meuwissen et al. [6,7].

3.4. Interpreting Value Distribution and Governance in the SocLab Model

The incorporation of marketing margin analysis and Transaction Cost Economics (TCE) can be articulated within the SocLab framework by linking economic outcomes and governance choices to its core elements—resources, stakes, effect functions, and influence. In this context, marketing margins can be interpreted as an indirect consequence of the distribution of influence among actors, which in the model arises from the control of resources and the dependencies captured through stakes. Actors controlling highly relevant resources—such as market access, negotiation capacity, or water management—tend to achieve higher influence, enabling them to shape interactions and potentially capture a larger share of value along the chain; thus, simulated influence may be interpreted as an indirect indicator of actors' relative capacity to influence value appropriation within the chain. At the same time, the configuration of stakes reflects structural interdependencies: actors that depend heavily on resources controlled by others face limited bargaining capacity and, consequently, less favorable value appropriation, whereas actors with greater control over key resources are better positioned to capture value. Effect functions indirectly further inform how resource management influences both value creation and its distribution, as positive effects may tend to facilitate coordination and increase the overall surplus, while negative effects may reflect conflicts that affect how value is generated and shared. From a TCE perspective, these interaction patterns can be interpreted as responses to coordination problems, where high uncertainty or strong interdependencies—captured through stakes and effect functions—may be associated with higher coordination requirements and, indirectly, with higher transaction costs, leading actors to rely on more coordinated or trust-based governance arrangements. Overall, the joint analysis of influence, dependencies, and interactions allows the model to connect simulated social dynamics with value allocation and governance structures, providing a coherent explanation of coordination and resilience in the value chain.

It is important to note that the model does not directly estimate observed marketing margins. Rather, the distribution of influence is interpreted as an indirect indicator of the relative capacity of actors to shape coordination processes and potentially capture value within the chain. Consequently, the proposed interpretation should be understood as analytical rather than econometric.

3.5. Expert Interviews and Model Validation

Four experts participated in the study. Three experts contributed to the model construction through semi-structured interviews, while a fourth expert participated in the validation of the simulation results. Tables 1–3 provide the participants' profiles, their organizational backgrounds, approximate ages, their role in the study, and a list of examples of questions that inspired the interview discussions.

Table 1. Profiles of the three experts who participated in model construction. The approximate ages of the interviewees are 49, 46, and 76.

Summary of the Role of the Interviewee	Type of Organization Where They Work and/or Have Worked	Roles Played in the Interview
Role: as Producers and Exporters: definitions of the 8 model resources; solidarity among actors (adjusted Producers-Exporters from indifferent to a positive relationship, increased the weight of water to parity with Producers for Exporters); weights/stakes of Production, StrengthenMarket, Negotiation, TecFinSupport, and ArcticActors (various live adjustments); effects of Production on the 4 actors (including the inverse relationship between StrengthenMarket for Producers and Exporters' performance) and of Negotiation on Producers, WaterManagers, and the Public Sector. Suggested explicitly incorporating the safeguarding of phytosanitary heritage (SAG) within RegulInspecProdProc.	Fruits of Chile (Chilean Fruit Exporters Association)—Representative for the Coquimbo Region (2025–present). Experience: ASOEX A.G.—Director of the Coquimbo Development Program (2007–2021); Coquimbo SME Strengthening Program—Manager (2021–2024); Trinidad Exports; Strategos; Limagro. Agricultural Engineer (PUCV), MBA (UCN).	Producers and Exporters
Role as WaterManagers: (1) WaterManagers' solidarity—strong towards themselves (other Water Users' Associations), medium towards Producers, none towards Exporters, medium towards the Public Sector—proposed differentiating water from the rest (suggested ~0.3 for themselves specifically in the case of water, given the drought context). (2) WaterManagers' resource stakes on Arctic Actors (their own resource), Production (adjusted from 0 to 2, subtracting from PlanProvideWaterInfra), TecFinSupport (1), and RegulInspecProdProc (adjusted from 0 to ~1, monitoring of water theft). (3) Effect functions: Production = indifferent/horizontal (water supply determines production, not vice versa); Arctic Actors = increasing with a ceiling (limited by external, non-decisional factors); RegulInspecProdProc = linearly increasing (better monitoring is always better, especially in drought). PlanProvideWaterInfra = linear increasing (more infrastructure, better, given the regulated Elqui basin with the Puclaro reservoir).	Elqui River Oversight Board—Manager/Water Distribution Engineer (since January 2020). Previous experience: Regional Directorate of Hydraulic Works (DOH) (until 2011); then DOH central level as an external consultant; subsequently independent consultant on Irrigation Law and evaluation of water resource investment projects. Profession: Agricultural Engineer and Industrial Civil Engineer.	Water Managers
Role as ArcticActors and as WaterManagers: (1) Definition of the ArcticActors resource of WaterManagers (capacity to coordinate actors around the efficient use of water)—agreed, with legal nuances (Water Code, distinction between Water Users' Association vs. Irrigation Association vs. water communities, jurisdiction up to the intake). (2) Solidarity of WaterManagers: strong towards themselves (~60%) and towards the Public Sector (~40%), none towards Exporters and Producers (except for domestic use/irrigation). (3) Solidarity of the Public Sector: agreed, strong towards themselves and evenly distributed with Producers/Exporters/WaterManagers. (4) Recommended disaggregating the Public Sector actor by ministry/service (DGA, DOH, INDAP, SAG, CNR, CORFO, ProChile) given that each has very different functions. (5) Regarding the relevance of public sector resources: PlanProvideWaterInfra (water infrastructure, via DOH/CNR, Law 1123) is the most relevant, followed by RegulInspecProdProc (linked to the efficient use of water resources, not only for agricultural production). (6) It provided key historical background (Puclaro reservoir management, 2013 Integrated Water Resources Management Master Plan) as evidence of the public sector's coordinating role in water infrastructure.	General Directorate of Water (DGA), Ministry of Public Works (MOP)—Coquimbo Region. Regional Director of Water (1995–2021); 50 years of service at the DGA (1971–2021). Milestones: management for the construction of the Puclaro reservoir (water rights, 1994–2000), participation in the Integrated Water Resources Management Master Plan (2013), modernization of the regional hydrometric network, establishment of water user organizations, Corrales, Puclaro and El Bato reservoirs.	Water Managers and Public Sector

Note: UCN = Universidad Católica del Norte; PUCV = Pontificia Universidad Católica de Valparaíso; ASOEX = Association of Exporters of Chile; SAG = Agricultural and Livestock Service; DOH = Directorate of Hydraulic Works.

Table 2. Profile of the expert involved in model validation.

Age	Type of Organization Where They Work and/or Have Worked	Summary of the Role of the Validator
50	Catholic University of the North (UCN)—Associate Professor, School of Business; Secretary of Community Engagement. Previous positions at UCN: Vice-Rector of Strategic Development and Quality; Director of the Institute of Public Policy (IPP); Director of the School of Business; Director of the Master’s Program in Administration. Public sector: CORFO (Regional Director, Coquimbo), Ministry of Economy, Ministry of Finance, DIPRES, Regional Government of Coquimbo.	Perspectiva Pública Sector

Note: UCN = Universidad Católica del Norte; CORFO = Chilean Economic Development Agency; DIPRES = Budget Office (Dirección de Presupuestos).

Knowledge elicitation was conducted through semi-structured interviews inspired by the SocLab methodology [44]. The interviews did not follow a rigid questionnaire; instead, they were guided by a set of representative questions that served to structure the discussion while allowing the interviewer to adapt the conversation according to each expert’s knowledge and experience. Examples of these guiding questions are presented in Table 3, whereas the complete interview guide is available in the Supplementary Materials.

Table 3. Examples of guiding questions used during the semi-structured interviews.

Interview Topic	Purpose	Example Guiding Questions
Actors and resources	Identify the principal actors and strategic resources in the fruit agro-export value chain.	Which actors are essential for the functioning of the value chain? What resources are critical for achieving your objectives?
Resource control and dependencies	Determine which actors control each resource and identify dependency relationships.	Who controls this resource? On whom do you depend to access or use it?
Importance of resources (stakes)	Assess the relative importance of each resource for achieving the actor’s objectives.	How important is this resource for your activities? (0–10 scale).
Effect functions	Characterize how different management levels of each resource affect actor performance.	What would be the best, worst, neutral, and usual management of this resource? How would each situation affect your objectives?
Solidarity among actors	Identify the degree of positive or negative concern for the welfare of other actors.	Which actors are most important for your success? Whose success or failure affects you?
Model validation	Assess whether the simulation results are consistent with the real system.	Do the simulation results adequately represent the governance and behavior of the value chain? Which results are most realistic? Which could be improved?

3.6. Ethical Considerations

All participants provided informed consent prior to participation. They were informed about the study’s objectives, the voluntary nature of their involvement, and the measures taken to ensure anonymity and confidentiality. No personally identifiable information was collected. The study involved no experimental interventions or foreseeable risks, and all procedures complied with standard ethical principles for social science research involving human subjects.

4. Model Development

The information for model development was gathered through virtual interviews conducted on the Zoom platform. Three interviews, guided by a thematic script with open-ended questions, were carried out. The interviewees were selected through purposive sampling due to their extensive experience and involvement in the fruit agro-export value chain. They represented key organizational perspectives within the system, including producers, exporters, and water management institutions. The objective was not statistical representation but the elicitation of expert knowledge required to construct the interaction structure of the model. Examples of the guiding questions discussed during the interviews included:

1. What resources do you need to perform your tasks, to achieve your objectives?
2. On who do you depend to access each resource, in order to use it according to your own need? Who controls it?
3. How important is that resource for your own work?

The subsequent validation involved expert judgment through an interview with a seasoned professional in the public sector. Our data collection approach was adapted from the methodology presented by Sibertin-Blanc et al. [44]. More specifically, the values used to define solidarities, stakes, and effect functions were elicited from the expert interviews. During the interviews, participants were asked to identify the actors and resources involved in the value chain, describe dependencies among actors, assess the relative importance of resources for achieving their objectives, and characterize the expected effects of resource management on organizational performance. The qualitative information obtained was subsequently translated into the formal parameters required by the SocLab framework, following the methodological guidelines proposed by Sibertin-Blanc et al. [44]. Therefore, the values presented in Tables 4 and 5 represent a formalization of expert knowledge rather than arbitrary assumptions introduced by the authors.

Table 4. Solidarity values elicited from expert interviews and formalized according to the SocLab methodology. Each cell shows the intensity of the solidarity of the actor in the row towards the actor in the column.

Solidarity →	Producers	Exporters	WaterManagers	PublicSector
Producers	0.5	0.2	0.2	0.1
Exporters	0.2	0.5	0.2	0.1
WaterManagers	0.3	0.1	0.5	0.1
PublicSector	0.25	0.15	0.25	0.35

Note: The arrow indicates the direction of solidarity: from actors in rows to actors in columns.

Table 5. Stake distributions and effect functions derived from expert interviews and formalized using the SocLab framework. Each cell presents the interaction between actors mediated by the stakes and the effect functions. It shows (as a number) the stake of the actor (column) on the resource (row), and (as function) the effect of the resource on the actor's activity. Stakes in bold denote the controlling actor for each resource. The last column of the table indicates the relevance of each resource. Abbreviations are explained in the note below the table.

Effect	Producers	Exporters	WaterManagers	PublicSector	Relevance
Production	 1.5	 1.0	 0.0	 1.0	3.5
StrengthenMarket	 1.5	 0.5	 0.0	 0.5	2.5
Negotiation	 1.5	 0.5	 0.0	 0.5	3.5

	1.0	2.0	0.0	0.5	
TecFinSupport					4.5
ArticActors					10
RegulInspecProdProc					5
PlanProvideWaterInfra					6
AdviseFinaProdImprov					5
	1.0	1.0	1.0	2.0	

Note: Stakes shown in **bold** identify the actor controlling each resource. The effect functions illustrate the impact of resource management on the corresponding actor. Resource abbreviations are: ArticActors = Capacity to articulate actors around the efficient use of water; RegulInspecProdProc = Regulation and inspection of agricultural production processes; PlanProvideWaterInfra = Planning and provision of water infrastructure; AdviseFinaProdImprov = Financial support and advisory services for productivity improvement.

The interviewees identified four actors and eight resources, with actor names in bold font and resource names in italic letters. The controlled resources of each actor were specified below their name:

- Producers: constituted by the Federation of fruit producers of Chile (FEDEFruta) and National Agricultural Society (SAN).

Production: Capacity for producing goods derived from the land (fruits, vegetables, etc.) with high levels of national and international competitiveness.

StrengthenMarket: Ability to strengthen current markets, explore new markets and promote the commercialization of products in national markets.

- Exporters: Association of Exporters of Chile (ASOEX).

Negotiation: Ability to negotiate with distributors, international buyers and/or public and multilateral international organizations to maintain long-term relationships in accordance with international regulations and market access conditions.

TecFinSupport: Financing capacity and technical assistance resources for its associates and/or suppliers to meet the productive and ethical standards maintained throughout the fruit agro-export value chain.

- WaterManagers: Vigilance Boards or association of channelers.

ArticActors: Ability to articulate all actors around the efficient use of water (distribution of the resource by intermediating supply with demand).

- PublicSector: Includes several ministries and other institutions, such as the Ministry of Public Works-MOP (General Directorate of Water-DGA and Directorate of Hydraulic Works-DOH), Ministry of Agriculture-MINAGRI (National Irrigation Commission-CNR, Institute of Agricultural Development-INDAP, Agricultural and Livestock Service-SAG), Ministry of Foreign Affairs (ProCHILE), and Ministry of Economy (Corfo and Sercotec).

RegulInspecProdProc: Capacity to regulate and supervise activities linked to the entire production process in the agricultural sector.

PlanProvideWaterInfra: Ability to plan and provide water infrastructure works (accumulation, distribution and efficiency).

AdviseFinaProdImprov: Ability to finance and advise on improvements in productivity, efficiency and market access for producers and/or marketers.

Next, we describe the models' input: (i) solidarities between actors, (ii) effect functions of resources on actors, and (iii) distribution of actor's stakes on the resources. Due to space constraints, we will elaborate on one of each.

4.1. Solidarities Between Actors

Table 4 illustrates the solidarities between actors. As an example of how solidarity was determined, we explain Producers' solidarity towards other actors. Producers are highly dependent on all other actors, as the entire system benefits when in good condition, promoting common well-being. Therefore, Producers place half of their solidarity (0.5) on other actors and the remaining half on themselves. Additionally, due to the closer situation of Producers to Exporters and WaterManagers, they allocate a higher solidarity (0.2) to Exporters and WaterManagers and a lesser solidarity (0.1) to the PublicSector.

4.2. Stakes and Effect Functions

The degree of dependency of an actor on a resource is articulated through its stake and an effect function. The game among actors is shown in Table 5, where each cell presents the interaction between actors mediated by the stakes and the effect functions. The last column of the table indicates the relevance of each resource: the sum of the stake for the resource in each row. For instance, the distribution of stakes for Producers signifies the hierarchical importance of resources in achieving their goal: obtaining economic benefits from agricultural production. Conversely, for WaterManagers, the stake distribution reflects the resource hierarchy for efficient water storage and distribution. Meanwhile, the effect function, considering the potential values of a resource, indicates the impact of the resource on the actor for each value within its domain, which may be positive or negative. For example, increased regulation and inspection of the production system by the Public Sector (row 6 in Table 5) would exert a strongly negative effect on Producers but a markedly positive effect on WaterManagers.

Distribution of stakes: Each actor allocates a normalized sum of 10 stakes. The stake controlled by the actor is presented in bold font. The relevance column denotes the cumulative stakes assigned to each resource. While the resource managed by ArticActors is deemed the most relevant, the overall order of actors concerning influence potential is as follows: PublicSector, WaterManagers, Exporters, and Producers.

Effect functions: Each effect function, displayed in individual cells, features the x -axis representing cooperation in resource management by the controlling actor, and the y -axis indicating the range of resulting impediment or facilitation for the dependent actor. Most effect functions reveal no conflict among actors, except for RegulInspecProdProc, where the shape of the functions indicates a conflict between Producers and the other actors, given the generally different slope of the function.

Due to space constraints, we cannot elaborate on the stake distribution of all actors on the resources. However, we provide an illustrative example of Producers' stake distribution.

Distribution of stakes of Producers. All resources hold similar importance for Producers, given that production success depends strongly on all resources, not a singular one. However, three resources have slightly higher importance for Producers: the two resources they control (Production and StrengthenMarket), and the resource related to water management (ArticActors). The latter has a marginally higher stake (2.0) compared to the former two (1.5 each). Producers invest slightly more in the resources they control and

the water management-related resource due to water scarcity in the Coquimbo region. The stake for all other resources is uniform: 1.0.

Effect functions of Production on the actors: Production has a comparable effect on Producers, Exporters, and the PublicSector, consistently growing as the resource increases. The additional effect of an increase in Production remains constant for the PublicSector (the curve slope does not vary), whereas the impact on Producers and Exporters is less pronounced at low or high production levels. In other words, at the beginning and end of the horizontal interval, the slope of the curve is smaller. This is because a variation in Production when it is small or too high has a lesser impact on the situation of Producers compared to a variation in Production when it is sufficiently high but not excessively so. Conversely, the effect on WaterManagers is null, reflecting that WaterManagers do not require the Production resource for their duties (their stake in it is 0).

Table 5 shows that, in general, there is little conflict among the actors: when the impact of an effect function is positive (respectively, negative) for one actor, it is also positive (respectively, negative) or neutral for the other actors. One of the few conflicts arises around the resource “Regulation and Inspection of Agricultural Activities” (RegulInspecProdProc), managed by the public sector, leading to a conflict with producers, and partially with exporters, against the rest of the actors. Another noteworthy element in Table 5 is the high relevance of the resource “Articulation of Actors around Water” (ActicActors) managed by WaterManagers, and the low relevance of the resources managed by producers, especially their capacity to strengthen the domestic market. This suggests that producers might have little influence on the system, while those coordinating water management could wield significant power, despite handling only one resource. Although the relevance (high stakes) of a resource is directly related to the influence of the controlling actor, it is not the sole determinant of influence in a particular game configuration, as it also requires the effect of the resource on the actors, in that configuration, to be highly positive.

5. Results and Structural Analysis

This section presents the simulation results and the analysis of the model’s structure, with particular attention to power distribution, coordination dynamics, and their implications for resilience.

The indicators to be presented in Tables 6 and 7 and Figures 2 and 3 should be interpreted as measures of organizational performance and system configuration rather than as direct observations of economic or physical variables. Their value lies in revealing patterns of resource management, actor satisfaction, influence, and system stability that are relevant for understanding resilience in the fruit agro-export value chain.

Table 6. State of the resources and standard deviations for the regulated state. All values presented are the means of the variables for 500 runs, which is the case for all the tables through all the paper.

Resources	Averages	Deviations
Production	8.15	2.52
StrengthenMarket	8.28	2.27
Negotiation	9.09	1.36
TecFinSupport	8.17	2.2
ArticActors	8.54	1.62
RegulInspecProdProc	4.71	4.0
PlanProvideWaterInfra	9.12	1.19
AdviseFinaProdImprov	8.84	1.52

Table 7. State of the resources and satisfaction for several configurations of the model. The table shows the state of the resources (first eight rows), satisfaction of all actors (rows 9 to 12), and global satisfaction (row 13), for the following configuration of the base model: state of maximal and minimal global satisfaction (at which the total sum of the satisfaction of the actors reach the maximal and the minimal values, respectively) (columns 1–2 of the generated data), actor’s maximal satisfaction (columns 3–6), regulated state (column 7), Nash equilibrium (column 8).

	Max Global	Min Global	Max Prod	Max Exp	Max WaterM	Max PublicS	Simul	Nash eq.
Production	10.0	−10.0	10.0	10.0	10.0	10.0	8.1	10.0
StrengthenMarket	10.0	−10.0	10.0	8.0	10.0	10.0	8.3	10.0
Negotiation	10.0	−10.0	10.0	10.0	10.0	10.0	9.1	10.0
TecFinSupport	10.0	−10.0	10.0	8.0	10.0	10.0	8.2	8.0
ArticActors	9.0	−10.0	9.0	10.0	8.0	10.0	9.5	8.0
RegulInspecProdProc	3.0	−10.0	−2.0	1.0	7.0	4.0	4.7	4.0
PlanProvideWaterInfra	10.0	−10.0	10.0	10.0	10.0	10.0	9.1	10.0
AdviseFinaProdImprov	10.0	−10.0	10.0	10.0	10.0	10.0	8.8	10.0
Producers	87.4	−86.0	88.2	86.6	85.4	86.8	79.8	86
Exporters	89.7	−89.1	89.1	91.1	87.2	90.1	82.6	89.2
WaterManagers	88.9	−91.7	87.2	86.1	89.7	88.3	82.8	88.1
PublicSector	88.5	−91.5	85.8	86.6	87.7	88.6	81.8	87.3
GLOBAL	354.5	−358.3	350.3	350.5	350.0	353.8	327.0	350.6

Note: Max Prod = configuration maximizing Producers’ satisfaction; Max Exp = configuration maximizing Exporters’ satisfaction; Max WaterM = configuration maximizing WaterManagers’ satisfaction; Max PublicS = configuration maximizing PublicSector satisfaction; Simul. = regulated-state simulation results; Nash eq. = Nash equilibrium.

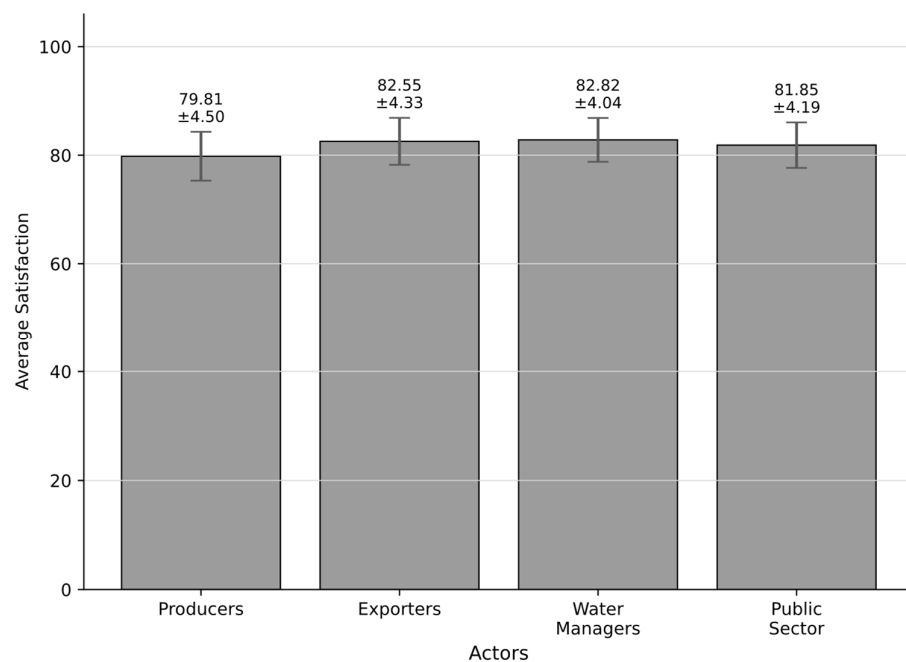


Figure 2. Distribution of satisfaction among actors in the regulated state. Values are means of 500 simulation replications; error bars indicate standard deviations.

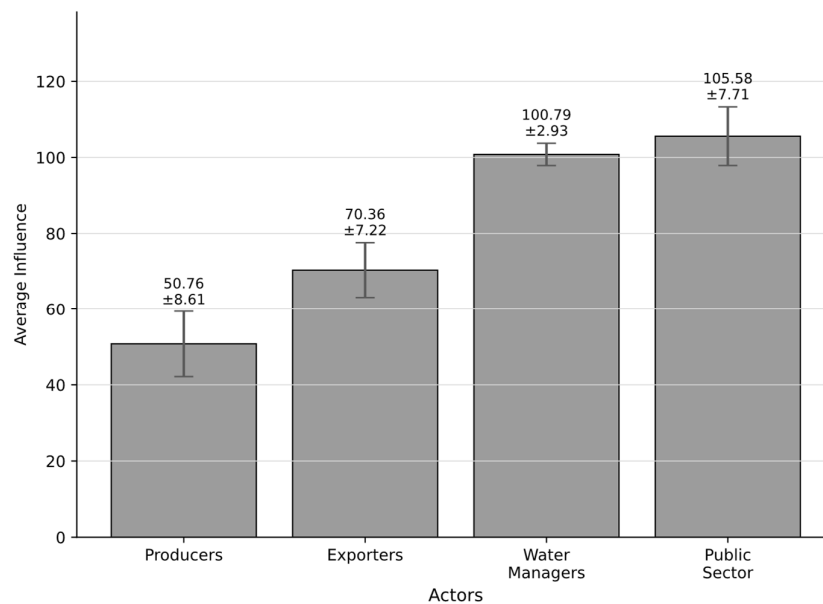


Figure 3. Distribution of influence among actors in the regulated state. Values are means of 500 simulation replications; error bars indicate standard deviations.

5.1. Simulation of the Model

The results of the regulated-state simulations (500 replications) are presented in Table 6 (resource states) and Figures 2 and 3 (actor satisfaction and influence). Overall, the standard deviations are relatively small, indicating stable simulation outcomes.

Table 6 presents the final values of the resources and their deviation from the regulated state. Resource values provide information about the condition of the resources within the organizational system, while deviations from the regulated state indicate the extent to which the system departs from a stable or desired configuration. Larger deviations may reveal tensions or weaknesses affecting the capacity of the system to maintain its functioning over time. In the context of resilience, these indicators provide information about the condition and stability of critical resources, particularly those associated with water management. Given the high number of replications, there is considerable confidence in the values of each result—a very narrow confidence interval could be constructed for each variable.

As observed in Table 6, most resources exhibit high values and relatively low deviations from the regulated state, suggesting a stable organizational configuration. The main exception is RegulInspecProdProc, whose lower value appears to reflect the conflict identified between Producers and the other actors regarding regulation and inspection activities. This result suggests that regulatory processes constitute one of the main sources of tension within the value chain.

Figures 2 and 3 present two complementary resilience indicators generated by the SocLab model. Figure 2 shows actor satisfaction, whereas Figure 3 presents the distribution of influence among actors. Satisfaction reflects the extent to which actors achieve their objectives within the organizational configuration. Influence measures the relative capacity of actors to affect the behavior of other actors and the overall functioning of the system. Together, these indicators provide information about the balance of power, the degree of actor satisfaction, and the stability of the organizational system, all of which are relevant dimensions of resilience. Figure 2 shows that actor satisfaction is relatively balanced across the four actors, suggesting that all actors achieve similar levels of organizational

performance under the regulated state. However, Figure 3 reveals a markedly different pattern, with influence being unevenly distributed among actors.

From a resilience perspective, this imbalance is important because participation in decision-making and the capacity to shape collective outcomes are not equally shared. Consequently, the system may be vulnerable to disruptions affecting the actors that control the most influential resources. Actors are ranked by influence as follows: PublicSector, WaterManagers (very similar to PublicSector), Exporters (approximately 70% of the influence of the two former actors), and Producers (approximately 50%). The high influence of the Public Sector is expected, since it manages several resources and performs coordination functions that benefit the value chain as a whole. The high influence of WaterManagers is particularly noteworthy because it results from the management of a single, yet highly critical, resource. The high influence of WaterManagers corresponds to its importance for agricultural productivity and water scarcity in the study region.

Exporters and producers, despite being central actors in the system, are not the ones with the greatest influence, indicating the high dependence of these two actors on the other two. This raises doubts about the autonomy of these actors, as well as the resilience of the agricultural system. Increasing drought intensity and growing water demand from other sectors of the socio-economic system further increase the vulnerability of the value chain and challenge its resilience.

5.2. Analysis of the Structure of the Base Model

Table 7 compares the states of resources and actors' satisfaction under alternative model configurations. The purpose of this comparison is to explore how changes in organizational arrangements affect the condition of critical resources and the satisfaction of actors. These comparisons provide insights into the sensitivity of the system to structural changes and help identify configurations that may contribute to greater resilience.

Table 7 indicates that when maximizing overall satisfaction or that of any actor, as well as for the simulation configuration and Nash equilibrium, all actors generally fare well (they have high satisfaction). Similarly, when minimizing overall satisfaction or that of an actor (not presented here due to space constraints), all actors fare poorly. It can also be observed that in the first case, the state of resources is very similar and high, except for the RegullInspecProdProc relationship, from which it can be deduced that the system's state is very stable (close to the best structural possibility that the system offers, i.e., maximum overall satisfaction). Therefore, in the simulation (regulated state), actors have no reason to want to change their situation and the state of the system.

The comparison of alternative configurations also shows that the regulated state is relatively close to the configurations associated with maximum collective satisfaction. This suggests that the observed organizational arrangement is not only stable but also comparatively efficient in terms of actor satisfaction. However, the persistence of influence asymmetries indicates that organizational stability does not necessarily imply an equitable distribution of power.

Given this stability and well-being of the actors in terms of satisfaction in the current structure of the system, the risks are low; in other words, in terms of structural aspects and satisfaction balance, the system has high resilience. Resilience risks lie in the imbalance of power and relevance in relationships. The latter is due to the high relevance of actor articulation and the set of relationships managed by the public sector, which, in turn, is associated with water scarcity and, in general, the vulnerability of the regional water system. These findings, as well as those of the previous subsection, also have implications for the sustainability of the system, as persistent power imbalances and resource constraints may undermine its long-term adaptive capacity.

These results can be read in terms of value distribution along the fruit agro-export value chain. The imbalance in influence suggests that actors controlling critical resources—particularly the Public Sector and Water Managers—are in a stronger position to shape coordination and capture a larger share of the value generated in the system. In contrast, producers and exporters, despite being central to production and commercialization, show lower levels of influence, which limits their capacity to negotiate and capture value. In this sense, the distribution of influence observed in the simulation suggests the existence of asymmetries in marketing margins across the fruit agro-export value chain.

At the same time, the strong dependencies observed among actors, especially around water-related resources, point to significant coordination challenges. These conditions are consistent with situations of high transaction costs, which help explain the central role of institutional actors and the need for coordinated forms of governance. The concentration of influence in actors managing key resources can therefore be understood not only as a power imbalance but also as a response to the need to stabilize interactions under conditions of scarcity.

5.3. Discussion

The analysis of the simulation and model structure reveals that the study system is in good condition, albeit with certain weaknesses due to resilience issues stemming from the imbalance of power among actors and the relevance of resources. Actors such as producers and exporters are weaker and have less capacity to influence export value chain decisions, increasing the system's vulnerability to external events, such as the current decrease in water availability. From a sustainability perspective, these vulnerabilities limit the system's capacity to maintain its functions under environmental and socio-economic pressures. The concentration of influence observed in the simulations is consistent with concerns raised by Clapp [50] regarding the effects of power concentration in agri-food systems. Although the present study focuses on a regional value chain rather than global food systems, both analyses suggest that asymmetries in decision-making capacity may create vulnerabilities affecting resilience.

Given that the issue of water availability originates externally to the fruit agro-export value chain (droughts in northern Chile, as well as demographic and economic growth), assessing its resilience requires considering various internal and external domains of the system and its resources [4,19]. Therefore, resilience involves not only the fruit agro-export value chain but also its broader context, including the socio-economic and water systems. Hereafter, this broader configuration comprising the value chain, the socio-economic system, and the water system is referred to as the extended system. Actors in the value chain must strengthen their participation within the extended system through greater collaboration, holistic thinking, and self-organization, thereby improving their capacity to influence decisions affecting critical resources. This interpretation is consistent with the recent resilience literature, which emphasizes that agricultural systems must develop adaptive capacities, learning processes, and the ability to reorganize in response to unexpected environmental and socio-economic changes [51]. As suggested by Vroegindewey and Hodbod [4], governance and participation are fundamental for the good performance and resilience of a system. The resilience indicators developed in this study suggest that the power imbalance among actors, the limited influence of producers and exporters, and the vulnerability of the water system together constitute a significant resilience challenge for the value chain. This result is also consistent with Vroegindewey and Hodbod [4], who identify participation and polycentric governance as key dimensions of resilience. The limited influence of producers and exporters suggests constraints on their ability to participate in decisions affecting critical resources, highlighting the importance of diversity, participation, learning, and adaptive governance as mechanisms for

coping with disturbances [42]. This situation suggests the need for corrective measures aimed at achieving a better balance of power and enabling the implementation of strategies to address water-related vulnerabilities. In this sense, greater participation may enhance the capacity of the value chain to adapt to changes in the water system and to increasing water demand from other sectors of society. The resilience of the value chain therefore depends on interactions occurring beyond the chain itself, involving broader social and ecological systems [52]. From a broader perspective, our findings show that the observed imbalance in influence is not only a governance issue but also a structural condition affecting how value is distributed along the chain. Actors with greater control over critical resources are better positioned to capture value, while more dependent actors face clear limitations. From the perspective proposed by Meuwissen et al. [7], the observed imbalances may reduce the adaptive capacity of the value chain, since adaptation depends on the ability of actors to influence decisions and respond collectively to changing environmental conditions.

The results can also be interpreted in light of recent frameworks on resilience in agricultural systems. According to Meuwissen et al. [7], resilience involves absorptive, adaptive, and transformative capacities. In our case, the relatively high levels of actor satisfaction suggest that the value chain is currently able to maintain its functioning under normal conditions, indicating a certain absorptive capacity. However, the imbalance of influence among actors and the strong dependence on water-related resources reveal limitations in its adaptive capacity, particularly in the face of increasing water scarcity and climate change. The central role of water-related resources reinforces findings reported in the resilience literature, which emphasizes that access to critical resources, together with adaptive governance mechanisms, constitutes a key determinant of the ability of agri-food systems to absorb disturbances, adapt to changing conditions, and maintain their long-term sustainability [1,7,51]. Consequently, improving participation, coordination, and the balance of power among actors may strengthen the ability of the system to adapt to future challenges. Furthermore, if environmental pressures continue to intensify, more substantial changes in governance and resource management may be required, corresponding to what Béné et al. and Meuwissen et al. [6,7] describe as transformative capacity.

From a practical perspective, improving resilience requires addressing power imbalances and strengthening coordination mechanisms. This includes enhancing participation, fostering trust, and supporting more balanced governance structures, particularly by empowering producers and exporters. Useful tools to achieve these objectives include strategic planning and foresight to anticipate future changes, such as increasing water demand and desertification in northern Chile, as well as simulation-based scenario analysis applied to the extended system. The proposed resilience metrics can be used to evaluate alternative scenarios and support decision-making processes. These tools may contribute to developing greater decision-making capacities among actors, fostering participation, learning, and self-organization, thereby strengthening participative or polycentric governance and improving the balance of power within the value chain. Such actions are consistent with the recommendations of Vroegindewey and Hodbod [4], particularly regarding the promotion of polycentric governance, holistic thinking, actor learning, self-organization, and adaptive decision-making. In the longer term, increasing environmental pressures may require more substantial institutional and governance changes, corresponding to the transformative dimension of resilience.

Taken together, these findings suggest that resilience in agri-food value chains depends not only on the availability of critical resources but also on the distribution of influence among actors and their capacity to participate in governance processes. Consequently, improving resilience requires addressing both resource constraints and

institutional asymmetries while strengthening the capacity of actors to participate in governance and collective decision-making processes.

5.4. Limitations and Future Research

As with any modelling exercise, this study has certain limitations. First, the model was developed from a limited number of expert interviews and therefore represents an expert-based analytical representation of the value chain rather than a statistically representative characterization of all stakeholders. Second, model validation relied primarily on expert knowledge and consistency checks, suggesting the need for additional validation procedures in future applications. Third, the analysis does not incorporate observed economic data, such as prices, costs, or actual marketing margins. Consequently, the interpretation of influence as related to value allocation should be understood as indirect and analytical rather than econometric. Finally, while the framework was applied to the fruit agro-export value chain of the Coquimbo region, future research should examine its application in other agri-food systems and geographical contexts to further assess the robustness, transferability, and generalizability of the proposed resilience indicators.

6. Conclusions

This paper proposes resilience metrics derived from a social simulation model based on the Sociology of Organized Action. By assessing the balance of power, actor satisfaction, and the relevance of key resources, these metrics provide a framework for evaluating resilience and sustainability in the fruit agro-export value chain of the Coquimbo region, Chile. The results show that resilience is weakened by power imbalances among actors and by dependence on critical resources, particularly water. While actors responsible for water-related resources and institutional functions concentrate influence, producers and exporters have limited capacity to shape decisions, reducing the system's ability to respond effectively to external pressures. The findings also indicate that resilience depends not only on the internal configuration of the value chain but also on its interactions with the broader socio-economic and water systems. By integrating social simulation with marketing margin analysis and Transaction Cost Economics, the proposed framework provides a broader understanding of how power distribution, coordination mechanisms, resource management, and value allocation jointly influence resilience in agri-food value chains. Overall, the proposed resilience metrics offer a practical approach for assessing and strengthening governance, sustainability, and resilience in agri-food systems facing environmental and institutional challenges.

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