

Article

The Institutional Anti-Commons in Antarctic Governance: A Network Evolutionary Game Analysis of Marine Protected Area Gridlock

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Abstract

Marine protected areas (MPAs) in the Southern Ocean are essential tools for marine conservation and Antarctic governance, yet new MPA proposals under CCAMLR have long struggled to become formal institutional outputs. This study conceptualizes this gridlock as an “institutional anti-commons”: under CCAMLR’s consensus rule, heterogeneous participating members possess de facto blocking capacity, while unresolved reservations may weaken the stability and implementation basis of agreement. To examine this explanation, we develop an institutional anti-commons framework and examine it through an agent-based evolutionary game model embedded in multiplex interaction networks. The model represents the 26 sovereign-state members of CCAMLR and distinguishes scientific participation, facility exposure, commercial fishery interest, sovereignty identity, and economic capacity. It compares a binary support–objection model with a conditional-support negotiation model, operationalizes agreement through a no-explicit-objection criterion, and evaluates transfer, pre-decision coordination, and network-layer specifications. Mechanism comparison shows that supporter-maintenance transfer alone has difficulty breaking gridlock, whereas interaction coordination more effectively reduces explicit objection. This study extends anti-commons theory to institutional decision-making and offers a diagnostic framework for understanding delays in institutional innovation in high-threshold international environmental regimes.

Keywords: Antarctic governance; CCAMLR; institutional anti-commons; agent-based modeling; evolutionary game theory; multiplex networks; consensus rule; marine protected areas

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1. Introduction

Marine Protected Areas (MPAs) have become a central instrument of global ocean conservation and area-based biodiversity governance [1,2]. Under Target 3 of the Kunming–Montreal Global Biodiversity Framework, states committed to ensuring that by 2030 at least 30% of terrestrial, inland water, coastal, and marine areas are effectively conserved and managed through protected areas and other effective area-based conservation

measures [3]. Yet global progress remains far below this target: the Protected Planet Report 2024 shows that only about 8.4% of the world's ocean and coastal areas are currently within documented protected and conserved areas [4]. This gap underscores the importance of expanding effective MPAs, especially in areas beyond national jurisdiction and ecologically significant marine regions. The Southern Ocean is particularly important in this regard. The CCAMLR Convention Area covers 35,716,100 km², approximately 10% of the world's ocean area [5]. It is among the most ecologically significant marine environments on Earth, sustaining the Antarctic food web centered on krill and providing critical habitats for penguins, seals, whales, and seabirds. It also plays an important role in global climate regulation and biological carbon transport [6–9]. Recent research estimates that Antarctic krill fecal pellets can sequester about 20 MtC during the productive austral spring and summer seasons [10].

To govern this ecosystem, the Convention on the Conservation of Antarctic Marine Living Resources (CCAMLR), adopted in 1980, was integrated into the Antarctic Treaty System [11,12]. Unlike general fisheries management regimes, CCAMLR's institutional objective is not merely to regulate resource exploitation but to ensure the long-term conservation of the Antarctic marine ecosystem while allowing for "rational use." Marine Protected Areas (MPAs) serve as a crucial spatial governance tool within this institutional toolbox, translating CCAMLR's ecosystem approach and precautionary principle into long-term spatial protection arrangements [13]. The Ross Sea provides a representative example. As one of the most productive regions of the Southern Ocean, it supports more than 30% of the world's Adélie penguins, around 30% of Antarctic petrels, half of Ross Sea killer whales, one quarter of emperor penguins, and more than half of the South Pacific Weddell seals that reside there year-round [14]. The MPA established by CCAMLR in this region entered into force in 2017, covering more than 1.5 million km². Excluding areas beneath ice shelves, approximately 72% of the protected area is designated as no-take. Such large-scale protection is of considerable ecological significance for maintaining critical habitats, food-web structures, and biodiversity [15–17].

However, there is a pronounced gap between CCAMLR's institutional output and its conservation objectives. Although CCAMLR adopted a framework for establishing MPAs in 2011, to date, only two large-scale MPAs have been established within its Convention Area: the South Orkney Islands Southern Shelf MPA (2009) and the Ross Sea Region MPA (2016). Given that climate change, expanding fishery pressures, and cumulative ecological disturbances are intensifying, the existing protection network remains spatially fragmented and inadequate to cover the actual scale of ecological risks in the Southern Ocean [18–24]. Proposals for new MPAs in East Antarctic, the Weddell Sea, and the Antarctic Peninsula have been repeatedly tabled yet consistently blocked [15,25,26]. The gap between scientific urgency and institutional output continues to widen.

Explanations for the impasse over the establishment of Southern Ocean MPAs primarily focus on diverging national interests and geopolitical competition. First, different states hold conflicting positions on resource use and conservation, especially with regard to fisheries interests. Studies show that when the establishment of an MPA has no obvious impact on fishing interests, the relevant proposal is often adopted relatively quickly. However, when an MPA affects the fisheries interests of some states in the area, such conflicts of interest are often transformed into prolonged disputes over the meaning of "rational use," the sufficiency of scientific evidence, the scope and duration of the protected area, and arrangements for existing or potential fisheries [27–29]. Second, MPA negotiations are also shaped by broader geopolitical considerations. In the Antarctic context, member states' concerns over future resource access, strategic presence, institutional influence, and the interpretation of decision-making authority within the Antarctic Treaty System may also make them cautious about the establishment of MPAs. As a result, under the consen-

sus rule, objections concerning key issues such as the delineation of protected-area boundaries, the duration of protection, and the authority for MPA management can delay negotiations, lead to repeated revisions of proposals, and even prevent scientifically grounded MPA proposals from being adopted [12,30]. Even the Ross Sea Region MPA, which was eventually adopted, involved substantial political concessions during the negotiation process, including a reduction in more than 40% in the originally proposed protected area [14]. Although these studies have revealed the role of interest conflicts and geopolitical factors in the difficulties of MPA designation, they have paid less attention to why such disputes are repeatedly amplified under CCAMLR's institutional structure and ultimately result in a persistent shortage of MPA institutional outputs. Interest conflicts are not uncommon in international environmental governance, and the Ross Sea case also shows that disagreements can be mitigated through compromise under certain conditions. The real questions that need to be explained are: Why is such compromise so costly and difficult to replicate within CCAMLR? Why can objections from individual members repeatedly block scientifically well-developed MPA proposals and produce a persistent governance dilemma in which multiple MPA proposals remain pending for long periods?

Therefore, this paper reframes the impasse over the establishment of Southern Ocean MPAs as an "Institutional Anti-Commons." Under CCAMLR's consensus rule, participating members possess *de facto* blocking capacity: a maintained objection can prevent a substantive proposal from being adopted, although this capacity is not a separately codified veto right. The deadlock does not stem simply from insufficient scientific evidence or divergent member preferences but from the interaction of these divergences with the consensus rule. When this high-threshold rule interacts with heterogeneity in commercial fishery interests, scientific participation, sovereignty-related positions, and broader geopolitical concerns, objection or delay by a minority may prevent institutional output. The MPA impasse is therefore understood as a structural deadlock generated jointly by the consensus rule, member heterogeneity, and differentiated blocking capacity. Building on veto player theory, the rational-design literature on international institutions, and anti-commons theory [31–36], this study develops a dynamic framework for examining how such gridlock may be weakened. It addresses how a high-threshold consensus rule interacts with actor heterogeneity, multiplex interaction channels, and modeled mechanisms such as transfer and pre-decision coordination. To examine the institutional anti-commons explanation, this study constructs an Agent-Based Evolutionary Game Theory (AB-EGT) model embedded in a multiplex network and uses the 26 sovereign-state members of CCAMLR as model actors for simulation.

The remaining parts of this paper are organized as follows: Section 2 develops the theoretical framework of the institutional anti-commons. Section 3 introduces the data, network construction, and model mechanics. Section 4 presents the simulation results. Section 5 discusses the theoretical and policy implications. Section 6 concludes the paper.

2. Theoretical Framework

2.1. Institutional Anti-Commons: Conceptual Definition and Theoretical Basis

As noted in the Introduction, this study introduces the concept of the "institutional anti-commons" in order to address the core problem identified there, namely the persistent insufficiency of institutional outputs. This concept is built upon two theoretical pillars: the "tragedy of the anti-commons" and veto player theory.

First, the tragedy of the anti-commons provides the basis for the conceptual extension developed in this study. Heller [36] and Buchanan and Yoon [31] argue that when exclusion rights are excessively fragmented among multiple actors, resource use becomes systematically suppressed, resulting in "underutilization"—the mirror image of the "tragedy of the commons." Its core mechanism lies in the way dispersed exclusion rights raise co-

ordination costs, intensify transaction difficulties, and ultimately generate inefficient allocation and value loss [31]. Related studies in fisheries resource governance have also shown that when the management of access rights involves multiple interdependent actors, fragmented decision-making and coordination failure can lead to disorderly and inefficient resource use, thereby producing a form of “underutilization” analogous to that described in the anti-commons literature [37]. This study extends that logic from the domain of property rights to that of institutional decision-making. Although both the “institutional anti-commons” discussed here and traditional anti-commons theory seek to explain collective-action failures arising from fragmented rights in resource governance, their analytical focus differs fundamentally. Traditional anti-commons theory is concerned with how fragmented property rights raise coordination costs and thereby reduce the efficiency and scale effects of resource use. By contrast, this study focuses on how, under a consensus-based decision-making rule, *de facto* blocking capacity is dispersed among members, substantially raising the threshold for collective agreement and thereby suppressing institutional output. In the CCAMLR context, what is fragmented is not the exclusion right over a particular resource but the practical ability to block institutional proposals when explicit objection remains unresolved under the consensus rule. Correspondingly, what becomes “underutilized” is not the resource itself but institutional supply and innovation [34,38].

Second, veto player theory informs our explanation of why this consensus structure tends to produce persistent gridlock. Veto player theory holds that as the number of actors capable of blocking policy change increases, and as the preference distance among them widens, the set of policies capable of replacing the status quo—the “winset”—continuously shrinks [33]. In the case of CCAMLR, substantial differences among members in commercial fishery interests, scientific participation, sovereignty-related positions, and broader geopolitical concerns have already increased the difficulty of reaching compromise. At the same time, the consensus rule institutionally empowers more actors to block policy change. In practice, however, blocking does not always take the form of a formal “no” vote. To avoid the political costs of open confrontation, states often employ strategic delaying tactics, such as requesting additional scientific evidence, raising procedural objections, calling for indefinite postponement, or conditioning their support on unrelated concessions, which may generate or sustain *de facto* blocking capacity [15,39]. To further specify the dynamic process through which such blocking capacity is maintained or weakened, this study extends veto player theory in three ways. First, while traditional veto player theory is particularly effective in explaining why the space for policy change contracts, it pays less attention to how gridlock is reinforced or overcome through interaction processes. To address this limitation, this study embeds veto player logic in a multiplex network composed of foreign-policy proximity, economic interdependence, scientific collaboration, and geo-facility proximity and examines two counterfactual mechanisms: a funded supporter-maintenance transfer ledger and a pre-decision coordination process that biases learning toward current supporters. Second, whereas traditional veto player theory mainly focuses on the number of veto players in a formal institutional structure and the differences in their preferences, this study further emphasizes that under a consensus rule, formally equal members do not automatically generate equal blocking capacity. Rather, heterogeneity in fishery dependence, scientific investment, sovereignty sensitivity, and geopolitical orientation transforms formally equal participation under the consensus rule into differentiated *de facto* blocking capacity. Third, this study incorporates a more realistic decision space by extending the binary “support–oppose” choice in traditional veto player theory to include a third possibility, namely conditional support.

2.2. Analytical Framework of the Institutional Anti-Commons

Building on the conceptual definition above, this study further translates the “institutional anti-commons” into an operational dynamic analytical framework to explain how de facto blocking capacity interacts with member heterogeneity in the CCAMLR context and ultimately leads to the persistent undersupply of institutional outputs for marine protected areas. To avoid terminological ambiguity, several related terms should be distinguished before specifying the framework. “Consensus rule” refers to CCAMLR’s decision-making practice in which formal agreement is difficult to reach when explicit objection remains unresolved. “No-explicit-objection criterion” refers to the operational criterion used in the model to code institutional agreement. “Explicit objection” refers to the strategy state that directly prevents agreement, whereas “conditional support” refers to non-objection with reservations, conditions, or unresolved concessions. “De facto blocking capacity” refers to the practical ability to prevent an institutional proposal from becoming a formal output when explicit objection remains unresolved under the consensus rule. Specifically, the framework consists of five interrelated elements: institutional rules, member heterogeneity, interaction structure, mechanism variables, and strategy space (Figure 1).

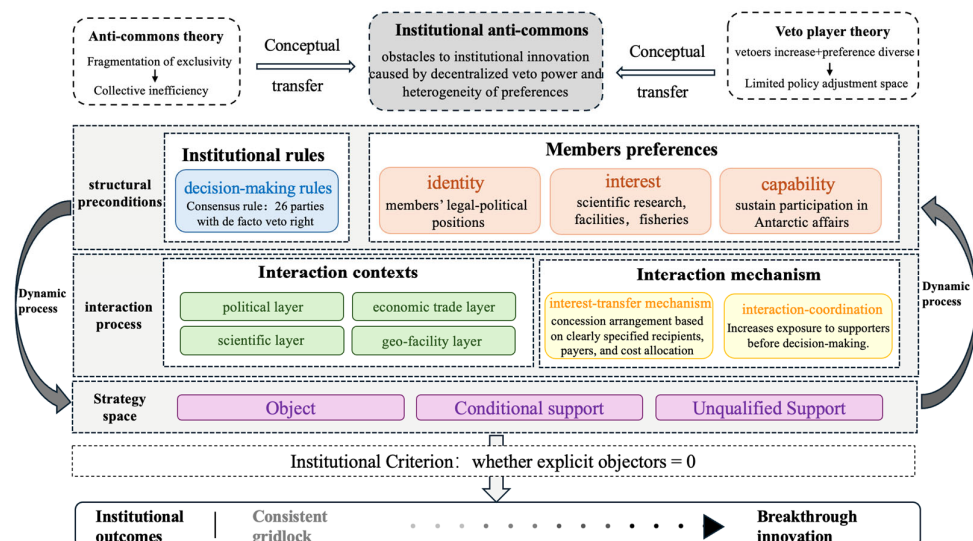


Figure 1. Theoretical framework for institutional anti-commons in CCAMLR governance.

First, institutional rules constitute the institutional precondition for the formation of the institutional anti-commons. CCAMLR’s consensus-based decision-making practice provides the institutional setting. For model purposes, agreement is operationalized through the no-explicit-objection criterion defined above. This reduced-form choice does not claim to exhaust the legal or diplomatic meaning of consensus in observed CCAMLR negotiations. In practice, reservations may also be expressed through requests for additional evidence, proposed revisions, procedural concerns, or postponement. Conditional support is not treated as explicit objection in the model, but it may still indicate unresolved reservations and a weaker basis for subsequent implementation.

Second, member heterogeneity determines how the above institutional rule is translated in practice into differentiated blocking capacity, thereby shaping the institutional output of MPA proposals. Although CCAMLR members operate under the same consensus requirement, the practical exercise and consequences of objection are embedded in differences in members’ identities, capacities, and interests. Specifically, the identity dimension primarily captures differences in members’ legal-political positions within Ant-

arctic governance, especially differences related to sovereignty status. The capacity dimension reflects differences in members' ability to sustain participation in Antarctic affairs, bear coordination costs, and maintain institutional action. The interest dimension captures the extent to which members are connected to existing institutional arrangements through scientific research, facility operation, and commercial fisheries. These differences generate distinct cost-benefit structures, risk perceptions, and strategic preferences [40–42] when members face MPA proposals, thereby narrowing the consensus space for such proposals. For example, members with stronger fishing interests may be concerned that protected areas will restrict fishing opportunities and future returns, leading them to express reservations, demand concessions, or lodge explicit objections [27–29,43].

Third, interaction structure specifies how member heterogeneity is transmitted among members and shapes the decision-making process. This study argues that CCAMLR members do not make strategic choices in isolation but are embedded in multiple relational contexts. The relational structures that persist among states shape actors' opportunities, constraints, and strategic choices [44]. On this basis, this study conceptualizes the interaction contexts among CCAMLR members along four dimensions. The political layer captures similarities among members' positions on broader international political issues [45]. The economic trade layer captures the mutual constraints and cooperative linkages formed through trade relations among members. The scientific layer captures cooperative relationships among members in Antarctic knowledge production. The geo-facility layer captures the spatial linkages among members created by the distribution of their Antarctic field facilities. Together, these four interaction layers characterize the relational contexts in which members observe, learn from one another, and adjust their strategies in terms of diplomatic positions, economic ties, knowledge collaboration, and Antarctic facility activities.

Fourth, interaction mechanisms are used to analyze how institutional gridlock may be weakened under given institutional rules and interaction contexts. Drawing on research on international cooperation, evolutionary games, and social learning, this study further introduces two mechanism settings. The first is the interest-transfer mechanism, which refers to a concession arrangement based on clearly specified recipients, payers, and cost allocation. Existing studies suggest that, under conditions of asymmetric member payoffs, reallocating the costs and benefits of cooperation may alter the payoff structure and strategic choices of specific actors, thereby affecting international cooperation outcomes [46,47]. The second is the interaction coordination mechanism, which operates before formal institutional outcomes are reached by increasing actors' probability of contact with, imitation of, and learning from supporters, thereby changing their interaction and strategy-updating processes [48–54]. The former primarily acts on the structure of interest distribution, whereas the latter primarily acts on the process of interactive learning. Based on these two mechanism settings, this study examines whether institutional gridlock may be alleviated under different conditions.

Fifth, strategy space captures the concrete action states of members under the above institutional and interaction conditions. Rather than simplifying consensus into a situation in which all members fully cooperate, this study uses the no-explicit-objection criterion to code institutional agreement and accordingly distinguishes among three strategy states: object, conditional support, and unqualified support. The introduction of conditional support means that members are not limited to a binary choice between explicit support and explicit objection but may participate in collective decision-making while retaining conditions, attaching additional demands, or offering only limited acceptance. In this sense, the institutional anti-commons is not constituted solely by open objection; it may also arise when explicit objection and conditional reservation jointly compress institutional output.

Taken together, the framework does not treat institutional rules, member heterogeneity, interaction structure, mechanism variables, and strategy space as separate elements

but links them into a sequential analytical logic. Actor heterogeneity and interaction structure provide the empirical basis of the model; mechanism variables are introduced under a given institutional rule to examine how different settings affect members' strategy states and simulated institutional outcomes. The institutional rule therefore functions both as the background condition of strategic interaction and as the criterion for judging whether a simulated outcome constitutes institutional agreement.

3. Materials and Methods

3.1. Study Area

This study examines the institutional process through which Southern Ocean MPA proposals have failed to reach agreement under the CCAMLR framework. The analysis focuses on the strategic interactions among the sovereign-state members of the CCAMLR Commission in relation to MPA proposals. The main model treats the 26 sovereign-state members of the Commission as the actor set. Although the European Union is also a Commission member, its competence and voting relationship with its member states require additional aggregation rules; therefore, it is not included as a separate actor in the main model. Accordingly, the main model does not cover all formal Commission members but uses the 26 sovereign-state members as the basic units of strategic interaction.

To assess whether the choice of actor set affects the results, a robustness analysis is conducted using a 25-state overlap sample consisting of countries that are both current CCAMLR Commission state members and Antarctic Treaty Consultative Parties. In addition, because the model incorporates facility exposure and facility-based spatial proximity, Figure 2 presents the spatial distribution of Antarctic research facilities as contextual background for interpreting the interaction network layer. The figure shows that research facilities are unevenly distributed across Antarctica, with visible concentrations around accessible coastal areas and historically active research regions, while large inland and remote areas contain fewer facilities. This spatial unevenness provides the empirical basis for constructing both facility exposure and geo-facility proximity in the model.

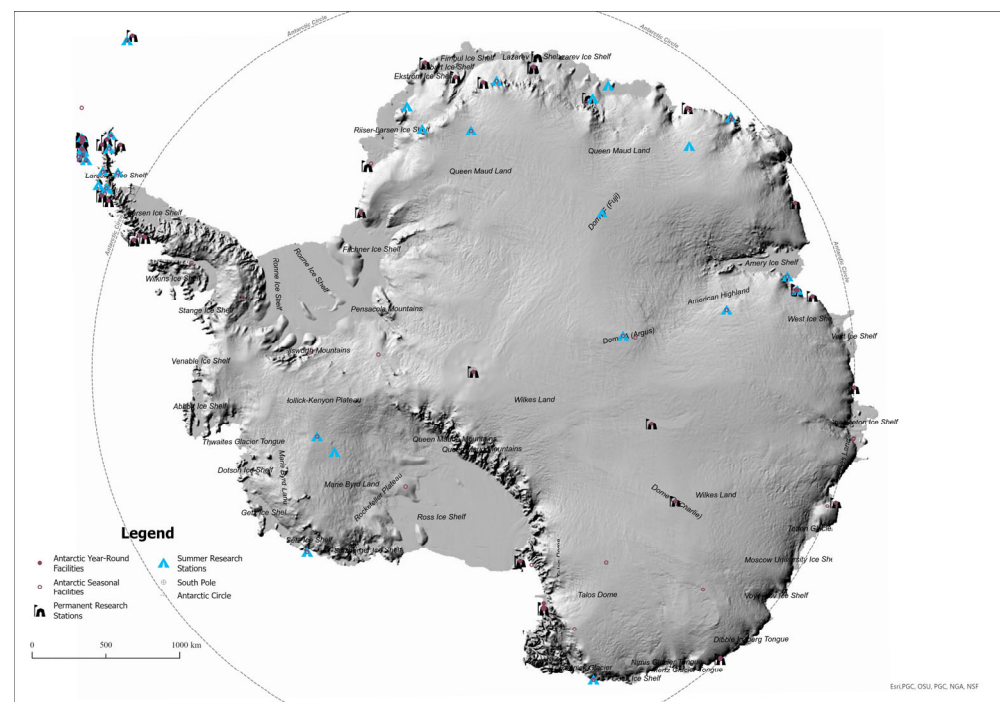


Figure 2. Spatial distribution of Antarctic permanent and seasonal research facilities.

3.2. Data Sources and Variable Selection

Following the theoretical framework, the analysis consists of five interrelated elements: institutional rules, member heterogeneity, interaction structure, mechanism variables, and strategy space. Member heterogeneity and interaction structure are constructed from external public data and serve as empirical inputs to the agent-based evolutionary game model. Institutional rules, mechanism variables, and strategy space are model settings and are specified in subsequent sections.

Member heterogeneity is conceptualized along three dimensions—identity, capacity, and interest—and is operationalized through five variables (Table 1). First, sovereignty identity (SOV) indicates whether a member is an Antarctic territorial claimant and is a binary variable capturing differences in legal–political position. Second, economic capacity (CAP) is constructed from 2024 current-dollar GDP data from the World Bank and captures members’ capacity to sustain Antarctic engagement, bear coordination costs, and maintain institutional action. Third, commercial fishery interest (FISH) captures members’ material association with existing resource-use patterns and is constructed from commercial or exploratory catch data for KRI, TOP, and TOA in the CCAMLR Statistical Bulletin for 2015–2024; research and survey catches are excluded from the main indicator. Fourth, scientific participation (SCI) captures members’ participation in Antarctic knowledge production and is constructed from Antarctic-related Web of Science (Clarivate, London, UK) records for 2016–2024. Fifth, facility exposure (FAC) captures members’ on-site operational presence in Antarctica and is constructed from the number of open and year-round facilities in the COMNAP Antarctic Facility Catalogue.

The interaction structure is represented by four network layers [55,56]. First, the political layer is constructed from recorded UN General Assembly votes for 2015–2024 and captures similarity in members’ positions on general international political issues. Second, the economic trade layer is constructed from bilateral trade data from UN Comtrade and captures trade-based interdependence among members [57,58]; CEPII BACI data are used as an alternative source in the robustness analysis. Third, the scientific layer is constructed from cross-national Antarctic research co-authorship in Web of Science records and captures cooperation in Antarctic knowledge production. Fourth, the geo-facility layer is constructed from the coordinates of open Antarctic facilities in the COMNAP Antarctic Facility Catalogue and captures spatial proximity in members’ Antarctic facility layouts. These four network layers characterize interaction conditions from the perspectives of diplomatic position, economic connection, knowledge cooperation, and facility geography. The network layers and proxy variables are not treated as direct evidence of real diplomatic coalitions or negotiation positions inside CCAMLR. Rather, they are used as possible channels through which members may observe, learn from, and adjust strategies in a multilateral environmental governance setting [59–62].

Table 1. Member heterogeneity and interaction structure variables.

Theoretical Element	Sub-Dimension	Measurement	Data Source
Member heterogeneity	Scientific participation (SCI)	Number of Antarctic-related Web of Science publication records by member during 2016–2024, transformed and normalized for model input.	Web of Science, 2016–2024
Member heterogeneity	Facility exposure (FAC)	Number of open and year-round Antarctic facilities for which the member is the primary operator in the COMNAP catalog, transformed and normalized for model input.	COMNAP Antarctic Facility Catalogue, November 2024

Member heterogeneity	Commercial fishery interest (FISH)	Catch records or catch volume for KRI, TOP, and TOA commercial or exploratory fisheries during 2015–2024, transformed and normalized for model input.	CCAMLR Statistical Bulletin, 2015–2024
Member heterogeneity	Sovereignty identity (SOV)	Binary variable equal to 1 if the member is an Antarctic territorial claimant and 0 otherwise.	Classification of Antarctic claimant states
Member heterogeneity	Economic capacity (CAP)	Member GDP in current US dollars in 2024, used to define coordination-core alternatives and allocate transfer costs.	World Bank WDI, 2024
Interaction structure	Foreign-policy proximity (Political layer)	Ordinal-distance similarity based on recorded UNGA votes. Votes are coded as Yes, Abstain, and No; absences, non-votes, and missing records are treated as missing rather than abstentions.	UN General Assembly Voting Data Version 5, 2015–2024
Interaction structure	Economic interdependence (Economic trade layer)	Symmetric geometric interdependence index based on bilateral import–export totals and each member’s total trade with the world.	UN Comtrade, 2015–2021; CEPII BACI as robustness source
Interaction structure	Scientific collaboration (Scientific layer)	Cross-national Antarctic research co-authorship ratio based on bilateral coauthored records and each member’s Antarctic-related publication records.	Web of Science, 2016–2024
Interaction structure	Geo-facility proximity (Geo-facility layer)	Relationship strength constructed from the spatial distance between open Antarctic facilities, using symmetric nearest-facility distance between members.	COMNAP Antarctic Facility Catalogue, November 2024

3.3. Model Specification

An agent-based evolutionary game model [63–65] is constructed to simulate strategic interactions among CCAMLR members in MPA decision-making. The purpose of the model is not to predict whether a specific MPA proposal will be adopted but to test whether heterogeneous members embedded in a multiplex interaction structure produce persistent opposition under different mechanism settings, and whether simulated institutional outcomes change across mechanisms. Given the presence of conditional support in real CCAMLR negotiations, the study develops both a binary support–objection model and a conditional-support model. In both model variants, four scenarios are compared: no mechanism, interest transfer, interaction coordination, and the combination of transfer and coordination. The simulation runs for $T = 400$ generations. The first $B = 200$ generations are designated as the burn-in period and excluded from all reported outcome calculations, so that the summary measures describe later-stage model behavior rather than initialization-dependent transients. The remaining generations, 201–400, constitute the post-burn-in observation window. Each scenario is repeated 30 times independently to reduce the influence of random initial conditions and stochastic updating. The simulated frequencies reported below are not probabilities that real MPA proposals will be adopted; they are diagnostic results for comparing whether institutional gridlock can be weakened under different mechanism settings.

Spatial data preprocessing, spatial analysis, and visualization were performed using ArcGIS Pro 3.4.0 (Esri, Redlands, CA, USA). Other data processing, network construction, and model implementation were conducted independently using Python 3.11.14 (Python Software Foundation, Wilmington, DE, USA).

3.3.1. Institutional Outcome

The institutional outcome is operationalized using a no-explicit-objection criterion. Rather than requiring all members to express active support, the model codes agreement when no actor remains in the explicit-objection state. This is a modeling criterion and does not imply that observed CCAMLR consensus can be reduced to a single behavioral state. Let O_t denote the number of explicit objectors in round t . The institutional outcome is defined as:

$$A_t = \mathbf{1}(O_t \leq q) \quad (1)$$

Here, $A_t = \mathbf{1}$ indicates that an agreement is formed in round t , whereas $A_t = 0$ indicates non-agreement. The parameter q denotes the maximum number of explicit objectors that can be tolerated for an institutional agreement. In the main model, $q = 0$, meaning that modeled agreement requires zero explicit objectors. Positive values of q are used only for counterfactual analysis. The $q = 0$ setting is this study's operational representation of a high-threshold consensus setting and should not be read as a separate formal rule of CCAMLR.

3.3.2. Strategy Space

Two strategy spaces are specified. The first is a binary support–objection model, in which members can choose only explicit objection (object) or support in each round. This model captures the most parsimonious case in which the explicit-objection state determines the modeled institutional outcome. The second is a conditional-support model, which adds conditional support as an intermediate state between explicit objection and unqualified support. Conditional support indicates that a member has not raised an explicit objection and therefore does not directly block agreement but may still hold reservations, attach demands, or require unresolved concessions. This model is intended to represent, in reduced form, negotiation situations in which a member does not explicitly object but still maintains reservations. The three strategy states are therefore explicit objection (object), conditional support, and unqualified support.

The payoff that actor i receives from choosing strategy s in round t is assumed to depend on the institutional outcome, member heterogeneity, local interaction structure, the weighted prevalence of the same strategy, and mechanism variables. The general payoff function is:

$$U_{i,t}(s) = b_s + a_s A_t + d_s (1 - A_t) + \sum_k \beta_{s,k} x_{i,k} + \eta_s L_{i,t} + \zeta_s H_{i,t} + T_{i,t} - P_{i,t} \quad (2)$$

In this expression, $U_{i,t}(s)$ is the payoff to actor i in round t when choosing strategy s ; s denotes the available strategy state, including explicit objection, conditional support, and unqualified support; b_s is the baseline payoff of strategy s ; A_t is the institutional outcome in round t ; a_s and d_s capture the payoff effect of strategy s under agreement and non-agreement, respectively; $x_{i,k}$ is actor i 's value on member-heterogeneity variable k that enters strategy-specific payoff assumptions, including commercial fishery interest, scientific participation, facility exposure, and sovereignty identity. Economic capacity is not assigned a direct preference coefficient; it enters the model through the prespecified coordination-core definition and the allocation of transfer costs; $\beta_{s,k}$ is the coefficient of heterogeneity variable k under strategy s ; $L_{i,t}$ is actor i 's local support level in the multiplex network; η_s is the payoff effect of local support; $H_{i,t}$ is the weighted prevalence of actor i 's current strategy among surrounding actors; ζ_s captures the payoff effect of same-strategy prevalence; $T_{i,t}$ is the transfer received by actor i in round t ; and $P_{i,t}$ is the transfer cost borne by actor i in round t .

The coefficients in Table 2 are behavioral assumptions, not empirical estimates. They are used for conditional identification: the model tests whether persistent opposition can

be reproduced under a given direction of payoffs and a specified set of behavioral assumptions. The baseline values encode ordinal behavioral assumptions: successful agreement is most valuable for unqualified supporters, unresolved non-agreement makes objection comparatively attractive, scientific and operational exposure increase the payoff of support, and commercial fishery exposure and claimant status increase the payoff of objection or conditional support. The numerical point specification is therefore used as a transparent baseline scenario rather than as a validated parameter vector. Substantive inference is drawn from mechanism contrasts, actor-construct ablations, and global sensitivity analysis, which identify which assumptions carry the simulated outcomes and which do not.

Table 2. Payoff coefficients for the three strategies.

Strategy	Agreement	Disagreement	Local Support	Same Strategy	Actor-Attribute Coefficients
object	−0.5	0.2	−0.2	0.1	FISH 0.5; SOV 0.2
conditional support	0.5	−0.1	0.1	0.1	SCI 0.15; FAC 0.15; FISH 0.2; SOV 0.1
unqualified support	1.0	−0.5	0.3	0.1	SCI 0.3; FAC 0.3

The terms $L_{i,t}$ and $H_{i,t}$ are calculated from the four interaction network layers constructed above. For each network layer, the layer-specific local support level and same-strategy prevalence are first computed. The model then aggregates across the available layers using layer weights:

$$L_{i\ell,t} = \frac{\sum_j w_{ij\ell} s_{j,t}^{support}}{\sum_j w_{ij\ell}}, L_{i,t} = \sum_{\ell \in \mathcal{L}_i} \pi_{i\ell} L_{i\ell,t} \quad (3)$$

$$H_{i\ell,t} = \frac{\sum_j w_{ij\ell} \mathbf{1}(s_{j,t} = s_{i,t})}{\sum_j w_{ij\ell}}, H_{i,t} = \sum_{\ell \in \mathcal{L}_i} \pi_{i\ell} H_{i\ell,t} \quad (4)$$

Here, ℓ denotes one of the four network layers; $w_{ij\ell}$ is the relationship strength between actors i and j in layer ℓ ; $s_{j,t}^{support}$ equals 1 if actor j is in a support state in round t and 0 otherwise; and $\mathbf{1}(s_{j,t} = s_{i,t})$ equals 1 if actors i and j choose the same strategy in round t and 0 otherwise. In the aggregated terms, $\mathcal{L}_i$ denotes the set of available network layers in which actor i has positive observation ties; $\pi_{i\ell}$ denotes the normalized weight of network layer ℓ within actor i 's set of available network layers. The nominal probability of each available layer is 0.25 in the four-layer main scenario. If a layer is unavailable for an actor, the weights are renormalized across the remaining available layers.

3.3.3. Interaction Mechanisms

Two mechanism variables are introduced. The first is the interest-transfer mechanism. This mechanism is based on an explicit recipient, payer, and cost allocation rule and is used to simulate whether redistribution of cooperation costs and benefits affects member strategy choice under payoff asymmetry. In the model, the transfer benefit received by eligible recipients and the costs borne by payers are defined as follows:

$$T_{i,t} = \gamma FISH_i \quad (5)$$

$$K_t = \kappa \sum_i T_{i,t} \quad (6)$$

Here, γ denotes transfer intensity, $FISH_i$ is member i 's commercial fishery interest, and κ is the cost multiplier. Transfer costs are interpreted as the collective costs borne by

current unqualified supporters to maintain or expand the support base and are allocated among current unqualified supporters according to economic capacity.

The second mechanism is the interaction coordination mechanism. This mechanism takes place before the formal institutional outcome is realized. It does not directly alter actors' payoff functions; rather, it simulates whether increased contact, observation, and learning from current supporters change the strategy-updating process. Let α denote pre-decision coordination intensity, that is, the probability that an actor contacts and learns from a current supporter before updating its strategy. The main model sets $\alpha = 0.5$ and uses the five members with the highest economic capacity as the main coordination core; alternative core sizes and core definitions are examined in the robustness analysis. In each round of strategy updating, the focal actor samples, with probability α , a connected and currently supportive member from the predefined coordination core as the learning object; with probability $1 - \alpha$, the focal actor samples a neighbor through the standard layer-prioritized multiplex network process.

$$j \sim \begin{cases} \text{SupporterCore}(i, t), & \text{with probability } \alpha, \\ \text{MultiplexNeighbor}(i, t), & \text{with probability } 1 - \alpha. \end{cases} \quad (7)$$

Here, j denotes the learning object sampled by focal actor i ; $\text{SupporterCore}(i, t)$ denotes sampling from the preset coordination core among members that are connected to i and currently support the proposal; $\text{MultiplexNeighbor}(i, t)$ denotes sampling of a neighbor according to the standard layer-prioritized weighted multiplex-network procedure; and α denotes the strength of the interaction coordination mechanism.

3.3.4. Strategy Updating During Model Iteration

Member strategy updating follows the Fermi rule [52–54]. After payoffs are calculated, the focal actor adopts the sampled actor j 's strategy with the following probability:

$$\text{Pr}(i \leftarrow j) = \frac{1}{1 + \exp[-\beta(U_j - U_i)]} \quad (8)$$

Here, β denotes the sensitivity of strategy adoption to payoff differences. $U_j - U_i$ denotes the payoff difference between the sampled learning object and the focal actor. When $U_j - U_i$ is positive, actor j has a higher payoff than actor i , increasing the probability that i adopts j 's strategy.

The main outcome variable is the post-burn-in agreement frequency, calculated as the number of generations in the post-burn-in observation window for which no explicit objector remains, divided by $T - B$. Here, "post-burn-in" refers specifically to generations $B + 1$ through T ; it does not imply that the process has reached an absorbing equilibrium. This indicator measures how often institutional agreement appears under a given mechanism setting. It does not represent the real-world adoption probability of an MPA proposal; it is used to compare whether institutional gridlock can be weakened across mechanisms. In addition to the main outcome, the study also reports support share, conditional-support share, number of objectors, implementation support index, transfer costs, and final strategy distributions as auxiliary outcomes.

$$\bar{A}_{\text{post}} = \frac{1}{T - B} \sum_{t=B+1}^T A_t \quad (9)$$

Here, T denotes the total number of simulation generations, B denotes the length of the burn-in period, and A_t indicates whether agreement is reached in simulation round t . If there is no explicit objector in round t , then $A_t = 1$; otherwise, $A_t = 0$. With $T = 400$ and $B = 200$, Equation (9) averages agreement over generations 201–400.

4. Results

4.1. Formation of Institutional Gridlock: Institutional Rules, Member Heterogeneity, and Multiplex Interaction Structure

This section examines how institutional rules, member heterogeneity, and multiplex interaction structures jointly shape the formation and persistence of gridlock in the model. The analysis proceeds in three steps. First, the no-mechanism scenario is used to assess whether the model can reproduce persistent non-agreement under the no-explicit-objection criterion. Second, actor-attribute adjustments are used to examine how member heterogeneity affects the payoff basis of objection, conditional support, and unqualified support. Third, network-layer ablations are used to assess how alternative interaction structures condition the diffusion of strategies among members. Each formal simulation runs for 400 generations, with the first 200 generations treated as the burn-in period and excluded from the formal results. Each scenario is repeated with the same set of 30 random seeds to reduce the influence of random initial states and stochastic updating on scenario comparisons. To examine whether the late-stage simulations are relatively stable, a convergence check using 20 random seeds was conducted. The results show that the maximum change in mean support share between the last two 50-generation windows is 0.023, and the maximum change in agreement frequency is 0.033, indicating limited late-stage variation. The model does not assume that a fully absorbing equilibrium has been reached; therefore, small fluctuations in the late-stage runs are retained. The Monte Carlo intervals reported below represent only simulation variation across the 30 repeated runs [66].

4.1.1. Persistent Non-Agreement Under the No-Mechanism Scenario

Under the point specification, when the model includes only institutional rules, member payoff assumptions, and the multiplex interaction structure, and no additional mechanism is introduced, both model variants reproduce a persistent non-agreement state. In the no-mechanism scenario, neither the binary model nor the conditional-support model reaches a no-explicit-objection state after the burn-in period; the agreement frequency is 0 in both models. Mean support share also remains low: 0.040 in the binary model and 0.020 in the conditional-support model. The corresponding mean numbers of explicit objectors are 24.959 and 24.548.

This result shows that, under the model's no-explicit-objection criterion, institutional agreement does not require all members to be unqualified supporters. However, as long as explicit objectors persist, agreement cannot be formed. In other words, the gridlock in the model is not created by a strong assumption that all members must explicitly support the proposal. It appears even under the weaker rule of no explicit objection. The conditional-support model further confirms this point. Although a small conditional-support share appears in the no-mechanism scenario (0.036), it does not eliminate explicit objection. Thus, the baseline non-agreement state does not depend on treating all forms of non-support as explicit objection. Even when members are allowed to adopt conditional support, persistent non-agreement still emerges if no mechanism changes the interaction process.

4.1.2. How Member Heterogeneity Affects Persistent Opposition

Baseline gridlock is not generated automatically by institutional rules alone. It is closely related to how member heterogeneity enters the payoff structure. In the model, differences in commercial fishery interest, scientific participation, facility exposure, and sovereignty identity enter the payoff function as actor-attribute variables and affect members' choices among explicit objection, conditional support, and unqualified support. Counterfactual adjustments to these actor-attribute variables show that issue-related var-

iables—commercial fishery interest, scientific participation, and facility exposure—have more pronounced effects on simulated agreement outcomes (Figure 3).

Commercial fishery interest is an important payoff basis for maintaining explicit objection or conditional support. When the fishery coefficient in the payoffs for explicit objection and conditional support is set to 0, agreement frequency increases by 0.114 in the binary model and 0.135 in the conditional-support model. When the sign of the fishery coefficient is reversed, agreement frequency increases by 0.192 and 0.208, respectively. This indicates that, under the payoff structure specified in this study, the more commercial fishery interest strengthens the payoff of objection or conditional support, the harder it is to form institutional agreement. Conversely, when fishery interest no longer supports objection or conditional support, agreement frequency rises noticeably. This result is consistent with the theoretical expectation that resource-use interests compress the consensus space for MPA proposals.

Under the declared payoff specification, scientific participation and facility exposure are interpreted as proxies for members' connection to Antarctic knowledge production, on-site operations, and institutional maintenance. Notably, they are not direct observations of preferences or realized benefits. The ablation result shows that the simulated agreement outcome depends strongly on assigning these constructs a positive support-payoff role. When scientific participation and facility exposure are removed from the support payoff, agreement frequency falls to 0 in both model variants; the corresponding changes are -0.191 in the binary model and -0.424 in the conditional-support model. This means that, under the specified payoff structure, these variables provide a payoff basis for the support strategy. Once this source of payoff is removed, support is difficult to diffuse and institutional agreement is difficult to form.

By contrast, the independent effect of sovereignty identity is relatively limited. Removing the sovereignty-identity term changes agreement frequency by 0.029 in the binary model and 0.069 in the conditional-support model. Economic capacity (CAP) is not included as a direct preference coefficient in the payoff function; it is used primarily to identify coordination cores and allocate transfer costs. When all actor-attribute coefficients are set to 0, agreement frequencies fall to 0.034 and 0.202, respectively. These results further show that member heterogeneity is not merely a background description of gridlock; it affects the relative attractiveness of strategies through the payoff function and participates in shaping the formation and maintenance of institutional gridlock. Overall, under the point specification used here, simulated MPA-related strategy choices are more strongly influenced by issue-related variables such as commercial fishery interest, scientific participation, and facility exposure. Commercial fishery interest is directly associated with possible restrictions on resource use resulting from MPA establishment, while scientific participation and facility exposure are associated with members' investments and benefits in Antarctic knowledge production, on-site operations, and institutional maintenance. Sovereignty identity and economic capacity primarily capture members' legal-political position and general capacity for action, and their independent effects are comparatively smaller.

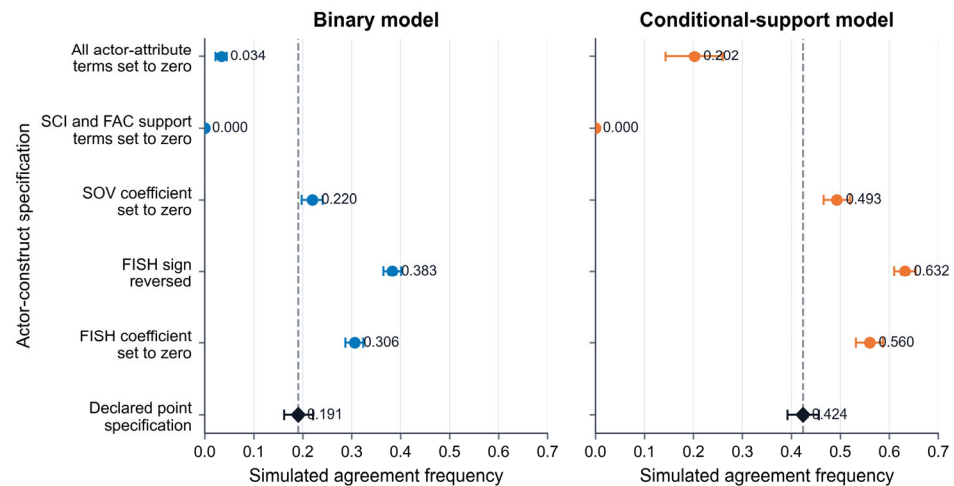


Figure 3. Effects of actor-attribute variable adjustments on agreement frequency.

4.1.3. How Multiplex Interaction Structure Conditions Strategy Updating in the Model

In addition to individual member heterogeneity, the interaction structure among members affects strategy choice. According to the theoretical framework, member decisions may be shaped not only by spatial association through facilities but also by relations with members that are politically proximate, commercially connected, or scientifically collaborative. The model examines the effects of four network layers—political, economic trade, scientific collaboration, and geo-facility proximity—on the strategy-diffusion environment. Specifically, the multiplex interaction structure enters the strategy-updating process through local support levels and same-strategy prevalence: network layers determine which actors a member is more likely to observe and learn from, while the support status and same-strategy distribution of those actors affect the member's subsequent strategy choice.

For comparability across network specifications, the network-layer ablation holds the mechanism setting constant and varies only the network-layer structure. The reported results use the combined-mechanism setting because it allows variation in agreement frequency across network specifications. As shown in Figure 4, under the four-layer network combination, the mean agreement frequency is 0.191 in the binary model and 0.424 in the conditional-support model. The study further examines differences in agreement frequency under alternative network specifications, including removing selected layers, retaining only a specific layer, using a uniform complete network, and using randomly permuted networks. The results show that, except for the “geo-facility layer only” scenario, which is notably lower, agreement frequencies under most other network specifications are close to those under the four-layer specification. This indicates that strategic interaction in MPA decision-making cannot be understood solely as spatial association through Antarctic facilities. If interaction among members is represented only by the spatial proximity of Antarctic field facilities, broader political, economic, and scientific relationship channels in MPA decision-making may be insufficiently captured.

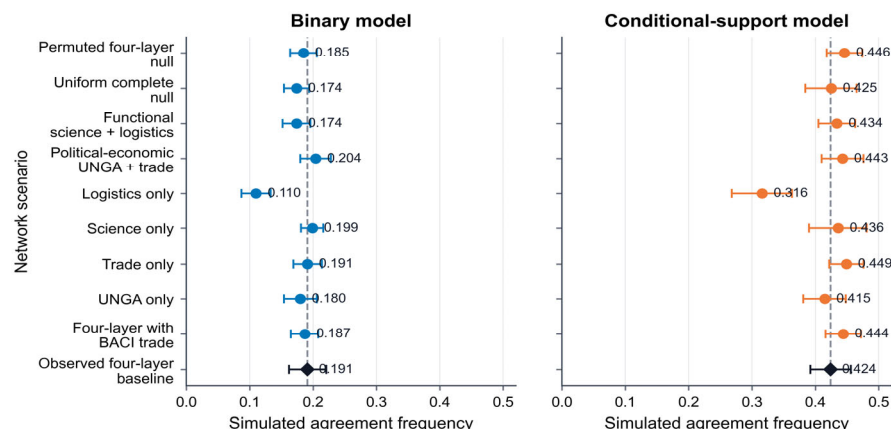


Figure 4. Network-layer ablation across the two network models.

4.2. Can Gridlock Be Changed? Comparing Interest Transfer and Interaction Coordination

This section compares two mechanisms that may alter gridlock: a transfer mechanism related to fishery interests and a coordination mechanism that changes the object of strategy observation through a coordination core. The former mainly responds to interest differences among members, while the latter mainly changes the process of strategy diffusion among members. By comparing four scenarios—no mechanism, transfer, coordination, and combined mechanisms—the analysis identifies differences in how these mechanisms affect agreement frequency, support share, and the number of explicit objectors.

As shown in Figure 5 and Table 3, the transfer mechanism alone does not substantially change the baseline gridlock. In the binary model, the no-mechanism scenario has an agreement frequency of 0, a mean support share of 0.040, and a mean number of explicit objectors of 24.959. After the transfer mechanism is introduced, agreement frequency remains 0, mean support share remains 0.040, and the mean number of explicit objectors is 24.953. In the conditional-support model, the no-mechanism scenario has an agreement frequency of 0, a mean support share of 0.020, a conditional-support share of 0.036, and a mean number of explicit objectors of 24.548. After the transfer mechanism is introduced, agreement frequency remains 0, mean support share is 0.019, conditional-support share is 0.039, and the mean number of explicit objectors is 24.499. Thus, under the implemented supporter-maintenance transfer ledger, transfers to eligible current supporters or conditional supporters are insufficient to remove explicit objection.

This result is related to how the transfer mechanism is specified. The transfer mechanism in this study is not a direct buyout of current explicit objectors or a form of pivotal objector conversion. Instead, it provides supporter-maintenance transfers to potential supporters with fishery interests, with costs allocated among unqualified supporters according to economic capacity. The transfer mechanism can alter some members' payoff structures, but it does not directly reduce the payoff that explicit objectors receive from the non-agreement state, nor does it directly change their strategy-observation targets. As long as explicit objectors remain, the model's no-explicit-objection criterion still prevents agreement. This suggests that, in a consensus-based, high-threshold institutional setting such as CCAMLR MPA decision-making, interest transfer alone does not necessarily break gridlock, especially when the transfer does not directly change the strategic attractiveness of objection.

By contrast, the coordination mechanism substantially increases agreement frequency. In the binary model, adding coordination increases agreement frequency from 0 to 0.201, raises mean support share to 0.912, and reduces the mean number of explicit objectors to 2.284. In the conditional-support model, agreement frequency under coordi-

nation increases to 0.473, mean support share rises to 0.935, conditional-support share falls to 0.023, and the mean number of explicit objectors declines to 1.091. This shows that the coordination mechanism not only increases support share but also substantially reduces the number of explicit objectors, making it easier to satisfy the agreement condition under the model's no-explicit-objection criterion. Coordination is more effective because it directly changes the objects that members observe and learn from during strategy updating. In the model, coordination does not enter members' utility functions as an additional payoff term; instead, it increases the probability that members observe a supportive core, thereby changing the strategy-diffusion process. When members more frequently observe actors with stronger support tendencies or stronger institutional action capacity, support becomes easier to diffuse and explicit objection becomes easier to weaken.

The results for the combined mechanism further show that transfer and coordination do not have a simple additive relationship. In the binary model, agreement frequency under the combined mechanism is 0.191, slightly lower than the 0.201 observed under coordination alone; mean support share is 0.907, and the mean number of explicit objectors is 2.424. In the conditional-support model, agreement frequency under the combined mechanism is 0.424, also lower than the 0.473 under coordination alone; mean support share is 0.903, conditional-support share is 0.034, and the mean number of explicit objectors is 1.625. In other words, under the point specification, adding transfer does not strengthen the effect of coordination and instead slightly lowers agreement frequency.

This does not imply that transfer mechanisms have no value in real governance. Rather, under the model specification used here, transfer has two limiting features. First, transfer costs are borne by unqualified supporters and may reduce the net payoff of the support state. Second, recipients are mainly potential supporters with fishery interests, not explicit objectors whose strategy attractiveness is directly altered. Thus, when coordination has already increased support share through strategy diffusion, adding transfer may not further reduce explicit objection and may instead weaken the payoff basis of unqualified supporters through cost sharing.

Table 3. Formal mechanism comparison.

Network Model	Mechanism	Agreement Frequency	MC 95% Interval	Support Share	Conditional Share	Mean Objectors
Binary model	No mechanism	0.000	0.000–0.000	0.040	0.000	24.959
Binary model	Transfer	0.000	0.000–0.000	0.040	0.000	24.953
Binary model	Coordination	0.201	0.172–0.231	0.912	0.000	2.284
Binary model	Combined	0.191	0.162–0.221	0.907	0.000	2.424
Conditional-support model	No mechanism	0.000	0.000–0.000	0.020	0.036	24.548
Conditional-support model	Transfer	0.000	0.000–0.000	0.019	0.039	24.499
Conditional-support model	Coordination	0.473	0.447–0.500	0.935	0.023	1.091
Conditional-support model	Combined	0.424	0.392–0.456	0.903	0.034	1.625

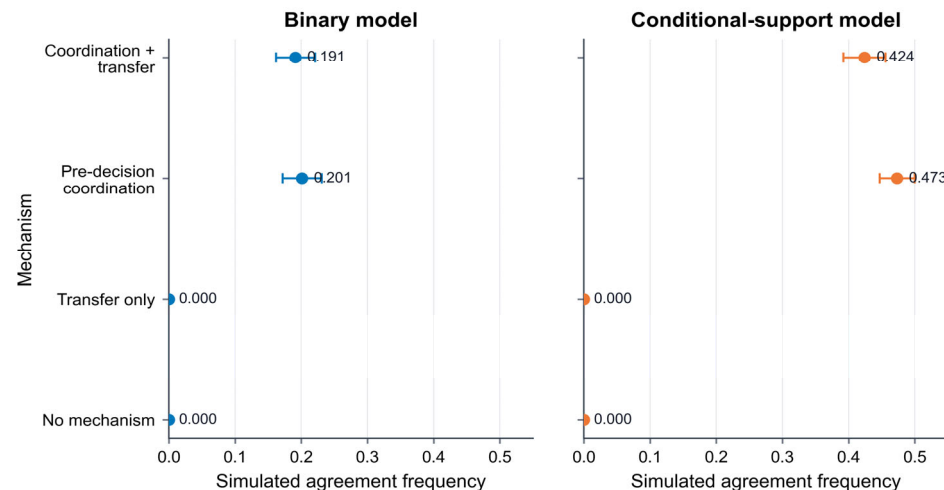


Figure 5. Mechanism comparison across the two network models.

4.3. Model Comparison and Robustness Checks

To examine whether the results depend on a particular variable measurement, actor sample, or mechanism specification, several robustness checks are conducted. These checks include four components: replacing the measurement of the trade network; adjusting the actor sample to examine whether the 26-member specification affects the main results; changing the definition of the coordination core; and conducting a global sensitivity analysis [67] to evaluate the direction and relative strength of key parameter effects on agreement frequency.

First, replacing the trade network measurement. In this robustness check, when the economic trade layer in the combined-mechanism scenario is replaced with CEPII BACI 2015–2024 data instead of UN Comtrade 2015–2021 bilateral trade data, the change in agreement frequency is small: -0.004 in the binary model and 0.020 in the conditional-support model, with corresponding intervals crossing 0. This indicates that the change in trade network data source does not alter the main simulation results.

Second, adjusting the actor sample. The actor-sample adjustment indicates that the main conclusions do not depend on the 26-member sample specification. The main model uses the 26 sovereign-state members of the CCAMLR Commission as actors and does not include the EU as a separate actor. To examine sample-boundary effects, a 25-state overlap sample is used as a robustness check. The results show that, in the 25-state sample, agreement frequency remains 0 under both the no-mechanism and transfer-only scenarios; the change intervals for the coordination and combined scenarios cross 0. This suggests that the main conclusion—that no mechanism and transfer alone do not break gridlock, while coordination substantially increases agreement frequency—does not depend on the specific 26-state actor set. This test is used only to assess differences between the 25- and 26-state samples; it does not resolve whether the EU should be modeled as a separate actor or whether broader institutional participants should be included.

Third, changing the definition of the coordination core. As shown in Figure 6, the coordination core in the main model is defined by economic capacity, using the top five members by CAP as the core. The robustness checks compare alternative definitions, including the top three by CAP, the top five by CAP, the top seven by CAP, and the top five by multiplex network strength. Under the combined-mechanism scenario, agreement frequency is approximately 0.175 – 0.196 in the binary model and 0.406 – 0.465 in the conditional-support model. Under coordination alone, the corresponding ranges are approximately 0.201 – 0.223 and 0.425 – 0.473 . Although specific values vary across core definitions,

the basic finding that coordination increases agreement frequency remains unchanged. This indicates that the coordination result is not caused solely by a particular definition of core members. At the same time, the definition of a coordination core remains a behavioral assumption in the model rather than an empirical identification of a real CCAMLR coordination coalition.

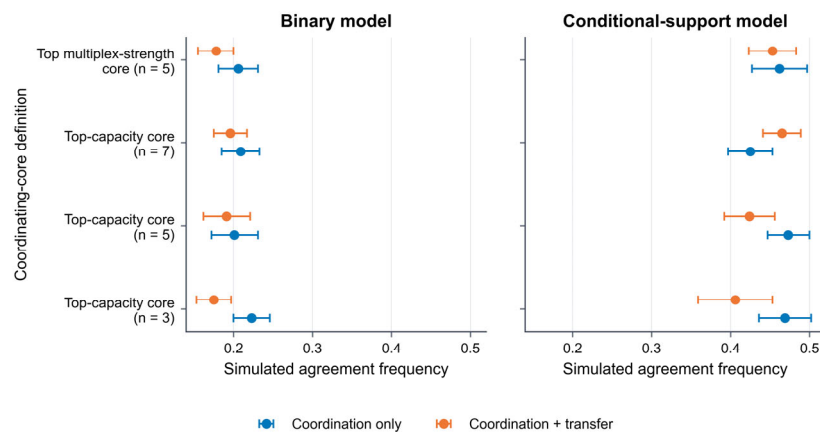


Figure 6. Coordination core robustness check.

Fourth, global sensitivity analysis. As shown in Figure 7, 128 Latin hypercube samples are used to examine model behavior under changes in key parameters. The results show that agreement frequency varies considerably across parameter combinations: the mean range is 0–0.66 in the binary model and 0–0.86 in the conditional-support model. The model results are therefore sensitive to some behavioral parameters and should not be interpreted as stable predictions from a single point specification. Partial rank correlation coefficients show that the payoff of the support strategy under non-agreement has the strongest positive effect on agreement frequency, with coefficients of 0.606 in the binary model and 0.560 in the conditional-support model. Mutation rate, the payoff of explicit objectors under non-agreement, and the fishery coefficient in the objection payoff have negative effects. The coefficients of scientific participation and facility exposure in the support payoff are generally positive, and coordination intensity has a moderate positive effect. Transfer intensity and the transfer-cost multiplier have weaker and negative effects. This is consistent with the mechanism comparison in Section 4.2: under the model specification used here, changing the diffusion conditions and payoff basis of support affects agreement frequency more than increasing transfer arrangements alone.

The robustness checks show that the main results are consistent across several alternative specifications: the no-mechanism and transfer-only scenarios fail to break the persistent non-agreement state, coordination substantially increases support share and reduces explicit objection, and the combined mechanism is not necessarily superior to coordination alone. At the same time, the sensitivity analysis shows that the model depends on key behavioral parameters, especially support-strategy payoff, objection-strategy payoff, the fishery-interest parameter, and coordination intensity. Therefore, the simulation results should be understood as a mechanism diagnosis rather than an empirical prediction of the probability that future CCAMLR MPA proposals will be adopted [68].

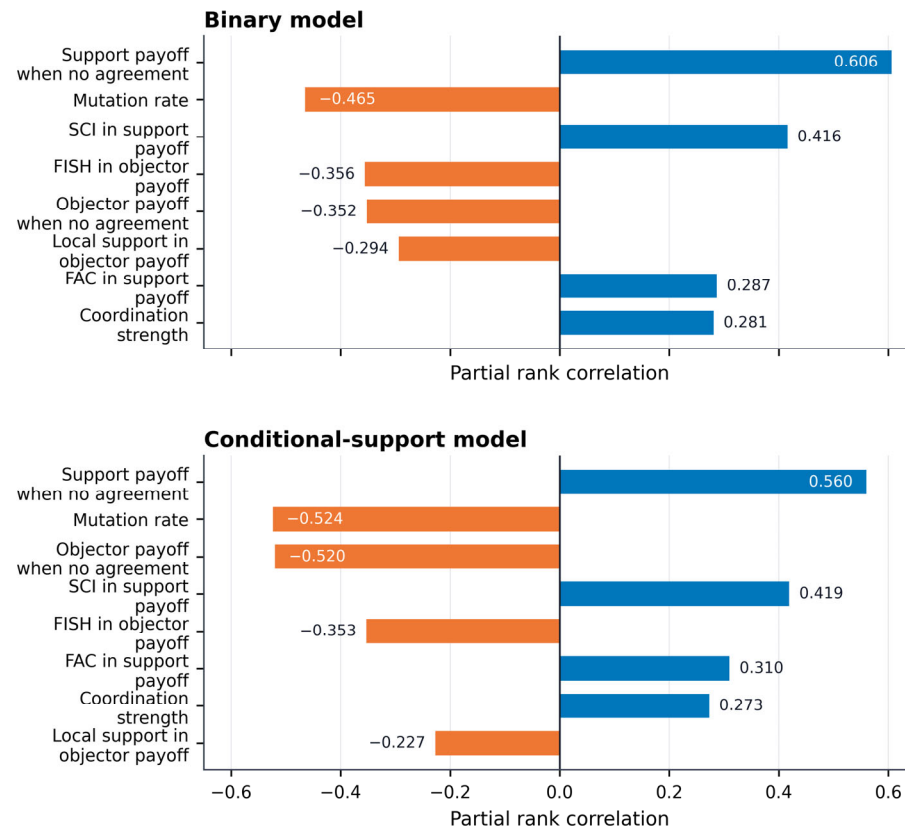


Figure 7. Global sensitivity of simulated agreement frequency.

5. Discussion

5.1. Mechanisms of the Institutional Anti-Commons

The institutional anti-commons model developed in this study explains why Southern Ocean MPA proposals under CCAMLR remain difficult to translate into formal institutional outputs despite long-standing scientific foundations and conservation needs. Rather than explaining why a particular proposal failed, the study addresses a more general institutional process: under the consensus rule, de facto blocking capacity interacts with member heterogeneity and multiplex interaction structures, thereby continuously constraining the space for institutional innovation. The “anti-commons” in this study does not refer to the underuse of Southern Ocean marine resources themselves. It refers instead to the suppression of a multilateral governance system’s capacity to produce spatial conservation rules and institutional arrangements—that is, insufficient institutional supply and institutional innovation.

The simulation results in Section 4 broadly support this explanation. The no-mechanism scenario shows that, even when consensus is not operationalized as “explicit support from all members” but instead as the weaker condition of “no explicit objection,” the model still produces persistent non-agreement. This indicates that institutional gridlock is not artificially created by an overly demanding consensus assumption. Rather, it can be generated by the joint effects of institutional thresholds, member payoff differences, and strategy-diffusion structures. The conditional-support model further shows that satisfying the no-explicit-objection criterion is not equivalent to unqualified support or sufficient implementation commitment. Members may remain in a state of conditional acceptance, reservation, or demand for further concessions. Although such a state does not directly

constitute explicit objection, it can still affect the stability of the institutional process and the basis for subsequent implementation.

This model first extends veto player theory in the explanation of institutional gridlock. Conventional veto player theory emphasizes that as the number of veto players increases and preference distances widen, the winset for policy change shrinks. Building on this logic, this study further shows that in consensus-based institutions such as CCAMLR, a common consensus rule may generate dispersed de facto blocking capacity, but this capacity does not operate among homogeneous members. As Section 4.1 shows, differences in commercial fishery interest, scientific participation, facility exposure, sovereignty identity, and economic capacity transform the same institutional rule into different strategic payoff structures. The model therefore extends the relatively static “preference divergence—winset contraction” logic of veto player theory into a dynamic process that includes payoff heterogeneity, strategy learning, and network diffusion.

The study also extends anti-commons theory. Traditional anti-commons theory primarily examines how fragmentation of property rights or exclusion rights leads to resource underuse. This study shifts that logic to the domain of institutional decision-making and emphasizes that when multiple members have the capacity to block institutional change, institutional output itself may be underproduced. In this sense, CCAMLR MPA gridlock is not merely a general failure of cooperation, nor merely the presence of conflicting interests among members. It is a process in which high-threshold decision rules transform minority objection or unresolved reservation into blockage of institutional innovation as a whole. The concept of institutional anti-commons thus explains why scientific evidence, ecological urgency, and conservation objectives do not necessarily translate into institutional outputs, and why prior compromise experience cannot automatically be replicated in new MPA proposals.

5.2. *Significance of the Institutional Anti-Commons Model for International Environmental Governance*

This study further connects the institutional anti-commons explanation with interaction processes in international environmental governance [60–62]. Existing studies of CCAMLR MPA gridlock often emphasize national interest divergence, fishery-resource conflict, geopolitical competition, or disputes over scientific evidence. These explanations identify the sources of member disagreement, but they less often explain how such disagreements are continuously amplified within institutional structures and eventually transformed into insufficient institutional output. This study incorporates institutional rules, member heterogeneity, interaction structure, and mechanism variables into a single dynamic analytical framework, showing that member disagreement becomes persistent blocking capacity only under specific rules and interaction structures. The multiplex interaction structure is not intended to identify a real diplomatic coalition. It is used to characterize possible channels through which members observe, learn from, and adjust strategies. Interest transfer and interaction coordination are used to examine the conditions under which such gridlock may be weakened.

The mechanism comparison further shows that institutional anti-commons is not a completely closed or immutable gridlock structure. It is a conditional institutional dilemma that depends on payoff structures and interaction processes. As shown in Section 4.2, the transfer mechanism alone does not break the baseline gridlock. This indicates that, in a consensus-based, high-threshold institutional setting, if transfer arrangements do not change the explicit-objection state and its payoff basis, merely adjusting the payoffs of some potential supporters is insufficient to produce an institutional breakthrough. By contrast, the interaction coordination mechanism changes whom members observe and learn from, making the support state easier to diffuse and reducing the number of explicit ob-

jectors. The further theoretical extension of the institutional anti-commons model is therefore that gridlock mitigation depends not only on the redistribution of interests, but also on the conditions under which support and objection states diffuse through interaction structures. In other words, the model not only explains how gridlock forms, but also provides a dynamic framework for analyzing the mechanism conditions under which gridlock may be weakened.

The study therefore explains the process through which “clear scientific demand but insufficient institutional output” arises in CCAMLR MPA decision-making and offers a scalable framework for analyzing institutional innovation delay in other high-threshold international environmental institutions. For Antarctic governance research, this framework helps move beyond binary narratives of “conservation versus use” or “science versus politics,” revealing how fishery interests, scientific participation, facility presence, sovereignty identity, and economic capacity jointly shape MPA decision-making under consensus rules. For broader international environmental governance research, the institutional anti-commons model provides an analytical tool for studying institutional innovation delay in high-threshold decision-making systems, especially those characterized by heterogeneous membership, dispersed de facto blocking capacity, complex interest structures, and strong scientific governance demands.

5.3. Policy Implications and Interpretive Boundaries of the Model

The results indicate that, under the model’s no-explicit-objection criterion, gridlock mitigation depends on whether relevant mechanisms can reduce explicit objection, stabilize the support base, and improve strategic interaction among members. On this basis, the study offers several cautious implications for the current Antarctic institutional gridlock.

First, analyses of MPA negotiations should distinguish more carefully among explicit objection, conditional support, unresolved reservations, and implementation commitments. The current CCAMLR difficulty is not a simple binary opposition between “support” and “objection.” MPA proposals for East Antarctica, the Weddell Sea, and the Antarctic Peninsula have been repeatedly submitted yet remain blocked, while the adoption of the Ross Sea MPA also involved long negotiations and political concessions. This indicates that institutional agreement is often affected by procedural objections, requests for additional scientific evidence, disputes over MPA boundaries and duration, fishery arrangements, and subsequent implementation commitments. Therefore, empirical research and policy evaluation of CCAMLR MPA negotiations should not code only “support” and “objection.” They should further identify explicit objection, conditional support, reservations, requests for modification, and implementation commitments. In policy practice, the goal should not be limited to achieving formal “non-objection”; it should also assess whether such non-objection can be translated into stable implementation support.

Second, interest-transfer or compensation arrangements need to be specified concretely. The simulations show that supporter-maintenance transfer alone does not break gridlock. This does not mean that concessions are ineffective in real governance. It means that if a transfer arrangement does not change the payoff that current explicit objectors receive from maintaining non-agreement, its effect may be limited. Real concessions may involve proposal-specific compensation, issue linkage, zoning adjustments, duration arrangements, targeted concessions, and implementation commitments. The adoption of the Ross Sea MPA was not based simply on general compensation; it was accompanied by sustained negotiations over protected-area extent, functional zoning, duration, and member-specific concerns. Policy attention should therefore focus on the concrete design of transfer mechanisms, including recipients, payers, cost sharing, monitoring mechanisms, trigger conditions, and enforcement constraints. Without credible and institutionally em-

bedded arrangements for monitoring, conditionality, and enforcement, simply increasing compensation or financial commitments may not change member strategies.

Third, pre-decision coordination and sustained interaction deserve attention, but the model-based coordination mechanism should be distinguished from real-world diplomatic coordination. As specified above, the model tests whether repeated exposure to currently supportive members with stronger coordination capacity can alter strategy diffusion and reduce explicit objection before formal decision-making. Economic capacity is used only as a simplified proxy for coordination capacity, not as a direct measure of diplomatic authority, persuasive power, or real-world leadership. The coordination core is therefore a behavioral modeling assumption rather than an empirically identified CCAMLR coordination coalition. In real CCAMLR negotiations, member strategy change may depend on fishery interests, scientific evidence, proposal design, zoning and duration arrangements, issue linkage, domestic sectoral preferences, diplomatic relations, and institutional precedent concerns. Real-world coordination is therefore better understood as a proposal-specific process, including prior consultation, joint scientific and technical work, iterative proposal revision, clarification of fishing-related concerns, and credible implementation commitments. The model result should be linked to reality only at the level of mechanism interpretation: under a high-threshold consensus setting, improving the pre-decision interaction environment may help expose reservations earlier, reduce information uncertainty, identify key disagreements, and narrow the space for explicit objection. Such coordination should not be understood as a small-group substitution for consensus, but as a process that improves proposal transparency, clarifies acceptable conditions, and reduces unresolved objections before formal decision-making.

At the same time, the interpretive boundaries of the model must be clear. First, agreement frequency is not the real-world probability that an MPA proposal will be adopted, and Monte Carlo intervals are not empirical confidence intervals estimated from real negotiation data. They represent only simulation differences among mechanism scenarios under a given model specification and repeated stochastic runs. Second, the political, trade, scientific, and geo-facility network layers should not be understood as direct evidence of real CCAMLR diplomatic coalitions or specific negotiation positions. They represent possible channels of observation, learning, and strategy adjustment among members, rather than identifying which network layer has a causally dominant effect on agreement formation. The network-layer adjustment results show that facility proximity alone is insufficient for representing member interactions, but they do not prove that political, trade, or scientific relations each have independent causal effects. In addition, the results cannot serve as a numerical basis for replacing consensus rules or specifying a particular voting threshold. Consensus rules may indeed suppress institutional output, but they also protect member voice, maintain institutional legitimacy, and reduce the risk of exit. Because the model does not endogenize member exit, compliance, or institutional legitimacy, it cannot evaluate the full trade-off between decision-making efficiency and institutional stability [26,69]. For an institution such as CCAMLR, which depends heavily on continued member participation, any discussion of decision-rule reform must consider institutional output, member acceptance, compliance foundations, institutional legitimacy, and long-term institutional resilience together [70,71].

6. Conclusions

The persistent blockage of Southern Ocean MPAs shows that, even when scientific necessity is relatively clear, institutional output may still be systematically constrained by decision-making structures. This study examines CCAMLR and defines this phenomenon as an institutional anti-commons: under consensus decision-making, *de facto* blocking capacity is dispersed among highly heterogeneous members, creating persistent barriers to

institutional innovation. The central question is not why one specific MPA proposal failed, but why this form of institutional blockage repeatedly appears within CCAMLR and why it is difficult to resolve through general compromise.

The study develops an agent-based evolutionary game model embedded in a multiplex interaction network to examine how institutional rules, member heterogeneity, interaction structure, and mechanism variables jointly shape MPA institutional outcomes. The simulations show that even when agreement is operationalized not as explicit support from all members but through the model's no-explicit-objection criterion, persistent non-agreement can still be generated. Differences in commercial fishery interest, scientific participation, facility exposure, and sovereignty identity enter the strategy-specific payoff assumptions and alter the simulated attractiveness of objection, conditional support, and unqualified support. Economic capacity enters indirectly through coordination-core definition and transfer-cost allocation. Political, trade, scientific, and facility-proximity channels affect the diffusion of support, conditional support, and objection. The mechanism comparison further indicates that supporter-maintenance transfer alone does not break the baseline gridlock, whereas pre-decision coordination and sustained interaction more clearly weaken explicit objection. The study therefore argues that CCAMLR MPA gridlock is not a single-factor cooperation failure, but an institutional anti-commons jointly generated by consensus rules, member differences, and strategic interaction. Its core features are that institutional rules distribute *de facto* blocking capacity among members, member heterogeneity shapes the payoff basis of objection or support, and multiplex interaction structures affect whether these states are maintained, diffused, or weakened. Understanding this process helps distinguish Southern Ocean MPA gridlock from the general narrative of interest conflict and directs attention toward an integrated analysis of institutional rules and interaction mechanisms. Future research should further develop proposal-level negotiation data [69,72–74] and incorporate proposal text, zoning design, issue linkage, targeted concessions, and implementation commitments into the analysis so as to examine more precisely how Southern Ocean MPA gridlock is formed and under what conditions it may be mitigated.

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Abbreviations

The following abbreviations are used in this manuscript:

Abbreviation	Full Form
AB-EGT	Agent-Based Evolutionary Game Theory
BBNJ	Agreement under the United Nations Convention on the Law of the Sea on the Conservation and Sustainable Use of Marine Biological Diversity of Areas beyond National Jurisdiction (also referred to as the High Seas Treaty)
CCAMLR	Commission for the Conservation of Antarctic Marine Living Resources (or the Convention of the same name)
COMNAP	Council of Managers of National Antarctic Programs
MPA	Marine Protected Area
CAP	Economic capacity
FAC	Facility exposure
FISH	Commercial fishery interest
SCI	Scientific participation
SOV	Sovereignty identity
UNGA	United Nations General Assembly
WDI	World Development Indicators
BACI	Base pour l'Analyse du Commerce International

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