Understanding the Emergence of Computational Institutional Science: A Review of Computational Modeling of Institutions and Institutional Dynamics

International Journal of the Commons

REVIEW ARTICLE

ubiquity press

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ABSTRACT

Computational Institutional Science (CIS) is an emerging stream of social science research performing institutional analysis with computational methods. While such scholarship is garnering increased attention, it draws on many different theories and engages disparate disciplinary backgrounds. Thus, this article provides an overview of CIS articles utilizing agent-based modeling, a computer simulation experiment method, to better understand critical theoretical lenses and topics. More specifically, this article clusters and analyzes 148 articles based on commonalities and differences empirically derived from their overlapping citations (i.e., citation cluster) and abstract content (i.e., topic cluster). Based on our analysis, we discuss the trends observed across cluster types and the overlap between them to better situate CIS inquiry.

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KEYWORDS:
Computational institutional science; Institutional analysis; Collective action; Social-ecological systems; Agent-based modeling Clustering analysis

TO CITE THIS ARTICLE:
Oesterling, N., Ambrose, G., & Kim, J. (2024). Understanding the Emergence of Computational Institutional Science: A Review of Computational Modeling of Institutions and Institutional Dynamics. *International Journal of the Commons*, 18(1), pp. 425–443. DOI: https://doi.org/10.5334/ijc.1335

INTRODUCTION

Understanding institutions is fundamental to understanding human behavior, since behavior is constrained, permitted, and required by the strategies, norms, and rules constituting institutions (Crawford and Ostrom 1995; March and Olsen 1989; North 1991; Ostrom 2005; Shepsle 1989). Over time, various approaches have been developed and engaged for the purpose of analyzing institutions and better understanding their effects of behavior; these include frameworks like the Institutional Analysis and Development (IAD) Framework (Ostrom 2005; 2011) and the Social-Ecological Systems (SES) Framework (Ostrom 2009; McGinnis and Ostrom 2014) and tools such as the Institutional Grammar (Crawford and Ostrom 1995; Siddiki et al. 2022). Existing research notes the potential of computational methodologies (e.g., agent-based modeling, text analysis) to complement existing approaches to institutional analysis (e.g., Ghorbani et al. 2013; Pieper et al. 2023; Siddiki and Frantz 2022) and scholars have increasingly leveraged these methods for such institutional inquiries (e.g., Olivier and Schlager 2022; Rice et al. 2021; Siddiki and Frantz 2023; Vannoni 2022).

The use of such computational methods to study institutions is, however, not new; rather, it is an approach which progressed across multiple academic traditions rather than as one cohesive body of knowledge. We adopt one of the names, suggested by Pieper and colleagues (2023), for this cross-disciplinary scholarship and refer to it as Computational Institutional Science (CIS). We define CIS as the use of computational methods to study the variety of institutions (e.g., rules, norms) within social systems (e.g., communities, workplaces, societies) and their outcomes (e.g., decisions, relationships) (Frantz and Siddiki 2022). Computational methods leveraged in CIS research include: (1) text analysis (i.e., automated review, extraction, and examination of textual data); (2) social network analysis (i.e., systematic investigation of interactions between different institutional actors); and (3) Agent-Based Modeling (ABM) (i.e., a computational experiment method that parameterizes and simulates interactions among actors with different characteristics in artificial environments and their emergent outcomes) (Edelmann et al. 2020; Pieper et al. 2023). This article focuses exclusively on CIS-ABM research (i.e., Computational Institutional Science research that utilizes ABM) to more effectively understand how CIS emerged and evolved along this dimension to study the development and outcome(s) of institutions. We focus on CIS-ABM scholarship for two reasons: (1) given the distinctness of each computational technique, to maintain comparability across articles; and (2) given the diffuse disciplines included in CIS, to maintain a narrow scope for this study.

While scholars have begun to retrospectively identify and discuss research that falls within our definition of CIS under a coherent label (Pieper et al. 2023; Siddiki and Frantz 2022), it has quickly become apparent that CIS investigations draw on a multitude of different disciplines (e.g., public policy, political science, economics, sociology, philosophy, law, computer science), perspectives (e.g., historical institutionalism, social institutionalism, rational choice institutionalism), frameworks (e.g., the IAD framework, the SES framework, Sabatier and Mazmanian (1980)'s policy implementation framework), and theories (e.g., common-pool resource theory, collective action theory, transaction cost theory) (Frantz and Siddiki 2022). Scholars note these broad scholastic traditions; however, studies engaging in CIS research often narrow the scope of their analysis to just one disciplinary lens (Pieper et al. 2023), potentially leaving the contributions of each discipline siloed from the insights of others (Frantz and Siddiki 2022; Siddiki and Frantz 2022). Despite calls to facilitate transdisciplinary discussions in this strand of research (e.g., Frantz and Siddiki 2022), to our knowledge, no study to date systematically examines whether intellectual silos indeed exist in CIS scholarship, and if so, what such silos look like and imply for future work in this stream of inquiry.

In this study, we begin to address this knowledge gap through a scoped review, and subsequent analysis, of existing scholarship that engages in Computational Institutional Science via agent-based modeling (CIS-ABM) approaches. Guiding our inquiry into potential siloing in this body of scholarship, are two overarching research questions. First, are scholars engaging in CIS-ABM research working within intellectual silos or, are they interacting and drawing upon different disciplinary traditions, theoretical framings, and conceptualizations? Second, if such CIS research is exhibiting the siloing suggested by previous literature, do any patterns of siloing emerge? To structure our investigation of these overarching questions, we pose a few, more narrow questions: (1) what patterns of theoretical traditions are observed when clustering articles based on overlapping citations (i.e., citation clusters), (2) what topical patterns are observed when clustering articles based on the content of their abstracts (i.e., topic clusters), (3) is there overlap between citation clusters and topic clusters that would indicate the presence of silos, and (4) what can be learned from these clusters and their overlaps? This article analyzes 148 research articles using clustering methods engaging network analysis and topic modeling. We leverage these methods as tools for identifying and exploring the intellectual orientations and topical foci of the research community engaging in CIS-ABM research.

COMPUTATIONAL INSTITUTIONAL SCIENCE AND AGENT-BASED MODELING

Institutions are defined in multiple ways, as the notion of institutions is foundational to many academic fields, particularly political science, sociology, and economics (Ostrom 2007). In this article, we define institutions as "enduring regularities of human action in situations structured by rules, norms, and shared strategies, as well as by the physical world" (Crawford and Ostrom 1995). Institutions constrain behaviors, prescribe actions, and evoke, and/or enforce relationships of individuals, producing desired outcome for a collective group (Frederickson et al. 2018; March and Olsen 1989; Ostrom 2005). While not exhaustive, some common examples of institutions are rules, laws, roles, norms, cultures, traditions, paradigms, and beliefs (Frederickson et al. 2018).

Researchers have studied institutions in many different domains and with various theoretical frames. Across the array of settings and styles for institutional analysis, the variety of institutions examined has been broadly categorized as exogenous – those that are designed and enforced by some hierarchical authority from a top-down perspective (Boettke et al. 2015; Dowsley 2008; Frantz and Siddiki 2022); and endogenous – those that emerge from a bottom-up perspective as a group of individuals engages in collective, grassroots processes of institutional development and implementation (Frantz and Siddiki 2022; Ghorbani and Bravo 2016; Greif and Laitan 2004). Hardin (1968) makes perhaps one of the earliest distinctions between these exogenous and endogenous orientations of institutions, arguing that reliance on voluntary, self-regulation (i.e., bottom-up, endogenously-developed institutions) for governance of a "commons" (e.g., a grazing pasture shared by cattle herders) is unrealistic and insufficient to prevent the depletion of a commonly-used resource. Instead, he contends that the superior way to manage shared resources is through the creation, application, and enforcement of rules (i.e., top-down, exogenously-imposed institutions) to constrain individual behavior and access to the resource(s) (Hardin 1968). Over time, however, scholars have observed endogenous institutions exhibiting effective governance of commons (i.e., common-pool resources); notably, Ostrom (1990; 2005) illustrates the capability of both institutional forms as well as the various institutions that constitute each.

As we demonstrate in later sections, CIS, like much of institutional science, has engaged various computational means for institutional analysis, studying both the emergence of endogenous institutions and the implementation of exogenous institutions (Choi and Park 2021; Frantz 2020; Siddiki et al. 2022). In our study, we examine how scholars have performed this computational institutional analysis through the use of ABM. ABM simulates human behavior within artificially-constructed populations and environments (Axtell 2000; Conte et al. 2012; Edelmann et al. 2020; Epstein 1999; Smaldino 2023). Broadly, ABM allows researchers to examine complex social systems through the reduction of these complex systems to more defined sets of rules. Miller and Page (2009) describe the 'true rules' of the social system as hidden from the researcher, and the complexity of those rules makes modeling them, even if they were observable, nearly impossible. As such, the goal of the researcher is to construct a simpler model that offers realistic insights to the real world but in a less complex setting. Identifying the 'smaller world' discussed by Miller and Page often starts by identifying the domain of the system being modeled, the context or specific concepts included in the model, as well as the means for operationalizing these concepts into the model.

In identifying and modeling these components of the "smaller world", conceptual accuracy and precision can be offered by institutional analysis approaches like the Institutional Analysis and Development Framework and its rule-based classification of institutions (Ostrom 2005) and the Institutional Grammar and its systematic dissection of institutional statements (e.g., rules, norms) into syntactic components and discrete semantic meaning (Crawford and Ostrom 1995; Frantz and Siddiki 2022). Thus, these CIS-ABM applications can help researchers move beyond traditional barriers in social science inquiry (e.g., one-time, self-reported data providing only a snapshot of social phenomena) and towards investigations of institutional phenomena with more depth, length, and breadth (Frantz and Siddiki 2022; Lazer et al. 2009; 2020; Siddiki and Frantz 2021). In particular, as scholars have further developed its capacity, ABM has become increasingly viable for: (1) exploring the emergent social patterns and equilibria of endogenous institutions and (2) building and evaluating theories through the simulation and replication of various dimensions of exogenous institutions (Gilbert and Terna 2000; Janssen and Ostrom 2006a; Smajgl et al. 2008). Thus, ABM can control for confounding factors surrounding decision-making within institutionalized settings and establish causality between changes in agents, interactions, environments, and emergent outcomes through computer simulation experiments (Bruch and Atwell 2015; Frantz et al. 2014).

SCOPE AND METHODS OF ANALYSIS

To identify relevant CIS-ABM articles, we searched the Scopus database for article abstracts containing key terms

(displayed in Table 1) related to institutional analysis and ABM practices. When using Scopus, we searched all combinations of the "Institutional Analysis" terms and "Agent-Based Modeling" terms in Table 1. As "institutions", "social-ecological systems", and "SES" are conceptualized divergently across disciplines, the "Filtering" terms were used to ensure the publications aligned with our study's definition of institutions. Citations (to use for citation clustering) and a full abstract (to use for topic clustering) are needed for the clustering analyses we perform; thus, papers without both were not studied. In addition, we manually checked whether each article conducts a computational experiment model in its ABM analysis to exclude any articles that that mention ABM, but do not engage in substantive modeling of institutions. Our final sample contained 148 distinct peer-reviewed articles and conference papers. Each sample text has an identification number (i.e., P#), which corresponds to Appendix *Table A1*. In *Table A1*, we highlight articles' respective citation cluster, topic cluster, and publishing journal.

INSTITUTIONAL ANALYSIS	AGENT-BASED MODELING	FILTERING
Institutional analysis and development framework	Computational modeling	Social
IAD	Computational method	Rules
Institutional analysis	Computational experiment	Norms
Institutional economics	Agent-based modeling	Strategies
Institutions	ABM	
Collective action	Simulation	
Social Ecological Systems	Parameter	
SES	Latent variable	
	Computer	
	Automation	
	Computation	

Table 1 Key Terms of Scopus Search.

CITATION AND TOPIC CLUSTERS OF CIS-ABM PUBLICATIONS

CITATION CLUSTERING THROUGH MULTI-LEVEL CLUSTERING NETWORK ANALYSIS

First, we cluster texts based on overlapping citations to explore the intellectual and theoretical orientations represented by these citations. We argue papers with more overlapping citations represent works with closer theoretical links compared to papers with few or no overlaps. Clustered papers are expected to be more theoretically similar than papers in different clusters. Finally, we contend that the clusters resulting from this analysis can help us emergently define intellectual and theoretical trends and can be used to better understand the multi-disciplinary influences of CIS.

The citations of all 148 publications were converted into a tabular database and constructed into a social network, where each paper was a node in the network and each tie represented an instance where: (1) two papers cited the same work or (2) one paper cited another work. If two papers cited multiple of the same works, the tie between these papers was weighted by the value of citation overlap, representing a stronger intellectual link. This process resulted in a social network where papers with greater citation overlap were more closely oriented to each other.

Given this weighted tie representation of the data, we utilize a multi-level clustering approach to identify the number of citation clusters and the allocation of texts into each cluster. We use a 'fast-and-greedy' hierarchical approach to cluster the citations which optimizes a quality function in a bottom-up manner. Initially, each paper belongs to its own cluster. At each iterative round of the model, connected nodes are merged to provide a locally optimal outcome which results in the largest increase in model fit. The model continues to greedily merge clusters until it can no longer increase the fit. This process results in n-number clusters of nodes, where all nodes are more similar to the nodes in its cluster than those outside its cluster. In practical terms, this means papers might have overlapping citations with papers outside of their cluster, but they have more citation overlaps with papers inside their own cluster.

Eventually, five distinct clusters emerged within our citation network. While many overlapping citations exist in each citation cluster, we identify the most cited text in each cluster, as shown in Table 2. In addition, we also explore the most cited first authors in each cluster.[1] This allows us to examine both the most popular works as well as the most popular scholars as identified by common citations in a cluster. Said works and scholars allow for an exploration of different disciplinary backgrounds from which CIS researchers draw.

We further utilize the citation clusters to better explore the differing theoretical orientations observed in CIS research by identifying conceptual and theoretical themes of these oft-cited texts and other popular works in each cluster. While Axelrod's *The Evolution of Cooperation* (Axelrod 1984) is the most cited work of *Citation Cluster*

CITATION CLUSTER	ARTICLE COUNT	MAJOR TEXT	COUNT OF CLUSTERED ARTICLES CITING MAJOR TEXT
(1)	29	Axelrod (1984) *The Evolution of Cooperation*	14
(2)	16	Ostrom (2005) *Understanding Institutional Diversity*	12
(3)	18	Axelrod (1986) *An Evolutionary Approach to Norms*	6
(4)	19	North (1990) *Institutions, Institutional Change, and Economic Performance*	12
(5)	61	Ostrom (1990) *Governing the Commons*	22

Table 2 Emergent CIS-ABM Citation Clusters.

#1, more generally, as a lead author, Axelrod is cited 30 individual times across all publications in this cluster, making him the most cited first author of Cluster #1. Other top authors in the cluster are Fehr (Fehr et al. 2002; Fehr and Gächter 2002), Nowak (Nowak 2006; Nowak and Sigmund 2005), and Ostrom (Ostrom 2000; Ostrom 1990). Collectively, these scholars are theoretically focused on the endogenous emergence of institutions. More specifically, they explore (1) the development of cooperation and punishment, (2) the rise of reciprocity, and (3) the evolution of social norms in group settings.

Although all three researchers investigate endogenous institutions and their evolution over time, disciplinarily, these scholars are diverse, representing economics (Ostrom), political science (Axelrod), behavioral economics (Fehr), and mathematical biology (Nowak). Works referencing *Cluster #1* focus on this cooperative, norm-based dynamics and outcomes of institutions within social phenomena. Dunbar's 2011 article (P39), for example, examines the constraints and evolution of social institutions in an ego-centric social network. By leveraging social simulations, Dunbar concludes that social dynamics likely limit the size of effective information exchange in networks. Helbing and colleagues (2011; P100) provide another example through their modeling of the co-evolution of social environments and individual behavior in the classic Prisoner's Dilemma, finding only when accounting for the combination of multiple social and cooperation mechanisms do stable macro-effects emerge.

Citation Cluster #2's most commonly cited work is Ostrom's *Understanding Institutional Diversity* (2005), which provides readers with the IAD framework for studying institutions. The framework offers a standard set of elements for empirically describing institutionalized situations. Other popular citations in this cluster are Crawford and Ostrom's (1995) work, first proposing the Institutional Grammar (IG) and Ostrom and colleagues' (1994) exploration of game theoretics in common-pool resource dilemmas. Both publications contribute to scholars' CIS toolbox, offering techniques and conceptual frames for systematically analyzing institutions. Outside of Ostrom's works, other popular publications are Gintis (2014), Simon (1990), and Kahneman (2011), and Kahneman and Tversky (2013). While Ostrom's works referenced in *Cluster #2* are focused on tractably identifying and measuring various institutions and their occurrence in social situations, the other commonly cited authors are more oriented on decision-making of the individual. Gintis argues the importance of game theory in understanding social systems (Gintis 2014), while Simon (Simon 1990) as well as Kahneman and Tversky (Kahneman 2011; Kahneman and Tversky 2013) identify patterns of 'non-rational' decision-making by individuals.

Citation Cluster #2, therefore, leverages divergent economic theories to define the exogenous institution and model decision-making within said institution. For instance, Zia and Koliba (2015, P77) simulate the outcomes of social-ecological systems by examining both exogenous drivers (i.e., multi-level institutional designs with distributed power) and endogenous processes (i.e., authority and decision-making arrangements). They find that changes to both exogenous and endogenous institutional factors result in significantly different resource allocation. Ghorbani and colleagues (2015, P13), meanwhile, use ethnographic data as a means to better define individual level decision-making within ABM models. In addition to exploring their own case, they offer a methodology for including such data in future ABM research.

Like *Citation Cluster #1*, *Citation Cluster #3* is also oriented around an Axelrod publication, although this time, the cluster revolves around "An Evolutionary Approach to Norms" (Axelrod 1986). *Citation Cluster #3*'s other top first authors are Searle (Searle 1995; Searle 1969), Zhao

(Zhao et al. 2013), and Sen (Sen and Airiau 2007). Searle's *Speech Acts: An Essay in the Philosophy of Language* (1969), identifies the philosophical implications embedded within language. More specifically, Searle's (1969) work examines the institutional construction of social reality in a community setting through constitutive rules. His work is influential in understanding how institutions, whether exogenous or endogenous, define conceptual constraints (i.e., the "rules of the game") and influence individual and collective behaviors. In complement to Axelrod's orientation towards norms, Zhao and colleagues' (2013) publication focuses on the dynamic spread of information in social groups, whereas Sen and Airiau (2007) examine the emergence of norms through the phenomenon of social learning in groups. Collectively then, *Citation Cluster #3* constitutes an interesting intersection of scholarly works conceptualizing institutions through framings rooted in philosophy and political science and operationalizing such concepts through means grounded in computer science and statistics. For example, Aldewereld and colleagues (2010; P99) examine the outcomes of simulated organizations to better understand the link between abstract organizational concepts and concrete norms. They argue the link between abstract organizational concepts (read as Seale's constitutive rules) is complex and susceptible to the contextual interpretation of an actor or an actor's choice to change the context. If actors interpret the context incorrectly or change the context, the concepts are not converted into a concrete norm.

In contrast, *Citation Cluster #4's* key works reflect a focus on understanding the endogenous institutions of large groups and phenomena. *Cluster #4* especially examines institutions amidst political and economic evolution and/or change. North and his work, *Institutions, Institutional Change and Economic Performance* (1990), are the most cited author and the major text, respectively for this cluster. Greif is the second most-cited first author in this cluster, with particular attention placed on his publication, *Institutions and the Path to the Modern Economy* (2006). This work, as well as that of other top cited authors, Acemoglu and Robinson (Acemoglu and Robinson 2013) and Williamson (Williamson 1998; Williamson 2008), highlight the cluster's narrower theoretical focus on institutions and their implementation in various contexts, particularly pertaining to economic performance and political participation. Frantz and colleagues (2015, P94; 2014, P95), for example, examine the role of apprenticeships and specialization, respectively, on the development of historical trader societies. They find social mechanisms, such as norms derived through apprenticeships, are able to predict social and economic changes that occurred between the 10th and 13th centuries. In an application with a more modern case, Razo (2021, P31) develops an equilibrium prediction using a computational model that helps explain rapid economic development in the absence of democratic institutions. This 'crony capitalism' model leverages networks of selective privilege and social connections among beneficiaries to derive these predictions.

In *Citation Cluster #5*, Ostrom's *Governing the Commons* (1990) was the most cited publication with other popular pieces including *The Tragedy of the Commons* (Hardin 1968) and *The Logic of Collective Action* (Olson 1965). The predominant texts in this cluster focus on the collective action problems of social and ecological systems rather than the institutional structures and decision-making as in *Citation Cluster #1*. These works explore questions of how individual behaviors can affect group outcomes, how institutional mechanisms (e.g., regulations, traditions) can guide individual behaviors to benefit the group, and how these institutions can fail or succeed depending on contextual conditions and individual perceptions. Under such theoretical lenses, work in *Citation Cluster #5* often examines the emergence of institutions in collective action and/or CPR settings.

Additionally, other oft-cited authors in this cluster are: Janssen (Janssen and Ostrom 2006a, Janssen and Ostrom 2006b), Wilensky and Rand (Wilensky and Rand 2015), Dietz and Liu (Dietz et al., 2003; Liu et al., 2007),and Holland (Holland 1995; Holland 2000). This set of commonly cited authors supplies the cluster's focus on computational modeling and computer science at the theoretical intersection of collective action, social-ecological systems, and advanced simulation. For example, work by Gutierrez-Garcia and Lopez-Neri (2015, P66) builds and applies a model of social deviance that works to more accurately represent the violation of rules governing artificial models. The rule-breaking models are meant to more accurately represent collective action situations and the tendencies to shirk and defect. Another publication, Ghorbani and Bravo (2016, P6), focuses more directly on a collective action situation. Using Institutional Grammar, they parameterize and simulate the sustainable management of a common-pool resource system by allowing agents to modify their own behaviors and strategies to establish a management institution.

TOPIC CLUSTERING THROUGH LATENT DIRICHLET ALLOCATION MODELING

In addition to clustering overlapping citations, we employ topic modeling to each article's abstract to examine different topics across our sample and better understand (1) the overarching topics emerging across all included papers, and (2) how individual papers are associated with emergent topic clusters. To do so, we utilize a Latent Dirichlet Allocation (LDA) (Bell and Scott 2020; Blei et al. 2003).

Broadly, topic models are used to identify co-occurrences of words within a corpus (or groups) of text (Grubert and Siders 2016). As groups of words are more frequently observed together within and across abstracts in the sample's corpus, words become associated with the same emergent topic. Topic clustering can, therefore, reduce data's dimensionality since many words are assigned to fewer, interpretable topics. LDA models use two levels of estimation to: (1) assign words to latent topics and (2) assign the same latent topics across documents (i.e., abstracts in the corpus) (Blei et al. 2003).

LDA models are run with different numbers of topics to examine how well the results fit the true distribution of words observed across the corpus. These coherence optimization procedures are used to identify the number of latent topics observed in the corpus. Figure 1 identifies the results of this optimization process. Higher coherence scores represent better topical fits to the probabilistic distribution of words in the corpus. As shown in Figure 1, the greatest coherence scores are observed with five topics, which we examine next.

While LDA modeling leverages rigorous probabilistic methods, it still relies heavily on human logic and interpretation (Bell and Scott 2020; Feuerriegel et al. 2016). Given the assignment of words to each topic, we identify each of the five topics based on the top ten words associated with each cluster, and by reviewing abstracts receiving high topic loadings (i.e., abstracts receiving proportional topic assignments close to 1). The topic cluster results, therefore, are supported statistically by the LDA process and qualitatively by abstract review.

The names and top ten words of each of the five topic clusters are presented in Table 3. Figure 2 illustrates the probabilistic assignment of topics to individual texts. Variation in color is associated with the abstract's assignment to one of the five topics based on its greatest loading score. Additionally, given the analysis, each abstract received a loading score for each topic. Abstracts with higher scores: (1) loaded more clearly into one topic, (2) had text more clearly associated with the topic, and, thus, (3) were identified as predominant texts of the topic. For example, P13's abstract most cleanly loads into *Topic Cluster #1* with very low loading scores on other topics. In contrast, P86's abstract has its largest loading score on *Topic Cluster #1* but has a similar score on *Topic Cluster #2*. This suggests that P86's topic, given this analysis, represents a mixture of both *Topic Cluster #1* and *Topic Cluster #2*, whereas P13 is clearly represented by the themes of *Topic Cluster #1*. P13 thereby topically represents *Topic Cluster #1* better than P86. Given the results of the LDA model and a review of high-loading abstracts, the topic cluster names are identified as: (1) Decision-Making and System Outcomes; (2) Societal Norms and Economic Institutions; (3) Group Dynamics and Emergent Institutions; (4) Natural Resources and Common-Pool Resources Management; and (5) Predicting Human Behavior. A list of all reviewed publications and their corresponding publication IDs (i.e, P#) can be found in Appendix Table 1. Appendix Tables 2 through 6 then break out these publications into their highest loading topic cluster.

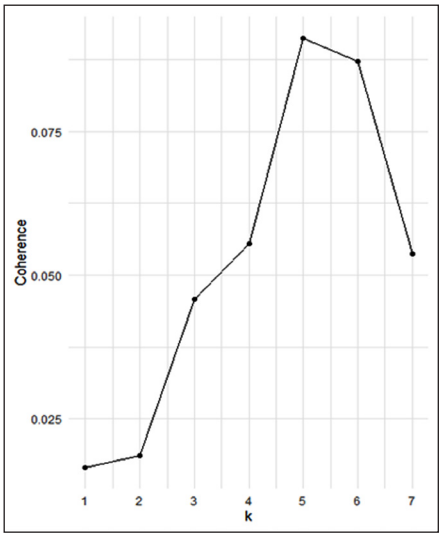

Figure 1 Coherence Scores.

Topic Cluster #1: *Decision-Making and System Outcomes* contains articles broadly focusing on modeling decision-making in complex social and ecological systems (P77, P13, P99), as well as the influence such decision-making — constrained by institutions — has on system outcomes (P14, P15, P33). A paper receiving a high loading score for *Topic Cluster #1*, Spies and colleagues (2014, P33), models the outcomes of fire-prone landscapes as a product of both ecological models and empirical studies of landowner decision-making developing to evaluate alternative management strategies. Another publication, Moncada and colleagues (2017, P14) examines the economic performance of biofuels of a product of both technical characteristics and the decisions and behavior of individual actors. The authors place emphasis on agent decision-making as they argue that past approaches have studied the performance of biofuels as a technical problem. Their models show that optimistic decision-making by investors influences the institutional changes needed to promote biofuel performance. Both papers exemplify *Topic Cluster #1's* orientation towards the topics of decision-making and systems outcomes, leveraging decision-making models of 'landowners' and 'investors' to help explain institutional changes in their respective simulations. These changes are subsequently engaged to examine different system outcomes as forest fire abatement or biofuel performance.

	TOPIC CLUSTERS				
	(1)	(2)	(3)	(4)	(5)
Cluster Name	Decision-Making and System Outcomes	Societal Norms and Economic Institutions	Group Dynamics and Emergent Institutions	Natural Resources and Common-Pool Resources	Predicting Human Behavior
Top 15 Words	agent	social	cooperation	resource	institutional
	social	norms	social	water	institutions
	agent_based	agents	group	management	change
	system	institutions	game	model	human
	institutional	society	behavior	resources	model
	making	agent_based	information	based	dynamics
	decision	rules	punishment	collective	scale
	policy	societies	network	action	time
	development	emergence	groups	local	behavior
	decision_making	order	individuals	community	simulation
	complex	informal	cooperative	common	dynamics
	simulation	work	organizations	social ecological	effects
	production	rule	evolutionary	collective action	modeling
	data	institutional	punishment	resource management	management
	models	social norms	network	emergency	performance

Table 3 Emergent CIS-ABM Topic Clusters.

Topic Cluster #2: *Societal Norms and Economic Institutions* orients on themes at a larger societal scale. For instance, publications in this cluster use ABM models to examine economic transitions (P94, P68), the emergence of norms in their stabilization or destabilization of societal equilibriums (P55, P83, P66), and the norms driving political stability (P73). Frantz and colleagues (2014, P68), explore the economic transitions of the Maghribi Traders Coalition and contemporary Genoese traders from different perspectives. More specifically, they examine how sustained cooperation within collective groups could emerge given different enforcement mechanisms through informal normative means. Savarimuthu and colleagues (2011, P55), meanwhile, focus on the importance of norms to stabilize societies. In their model, they explore how levels of norm learning can stabilize society equilibrium even with detrimental effects of liars in the society. Finally, Vallier (2017, P73) examines the political stability of a society as the equilibrium of individuals' willingness to comply with institutions. The model is built to reflect a 'well-ordered society' built on social trust and cooperation, as well as the ability to overcome short run variability and noncompliant actors. The individual examination of each of these components allows for a greater understanding of tradeoffs leading to politically stable societies. While each of these examples examine a different domain — economic transitions via institutional change, the ramifications of informal institutions on society stabilization, and the implications of institutional compliance on political stability — each examines the effect(s) of institutions at broader societal scales compared to the topics of other clusters. As such, each paper fits the theme of *Cluster #2*, which orients on equilibrium and stability in the modeled system.

Topic Cluster #3: *Group Dynamics and Emergent Institutions* focuses on promoting cooperative behaviors in a society with individuals as the main unit of analysis. Articles in this cluster assess how group size (P65, P39), altruism (P91), and reputation (P70, P49) can address first-order free-rider problems, arising because individuals decide to enjoy the benefits of collective goods without paying for the costs of provisioning those goods. Furthermore, other clustered articles examine how punishment (P53, P47) may help overcome the second-order free-rider problem, or a lack of dedication to enforce individual contributions to collaborative efforts among participants. Makowsky and Smaldino (2016, P91) examine the first-order free-rider problem of the influence of 'selfish' and 'altruistic' actors within and across groups. As more groups compete for resources, they find altruistic groups led by selfish individuals can outcompete other

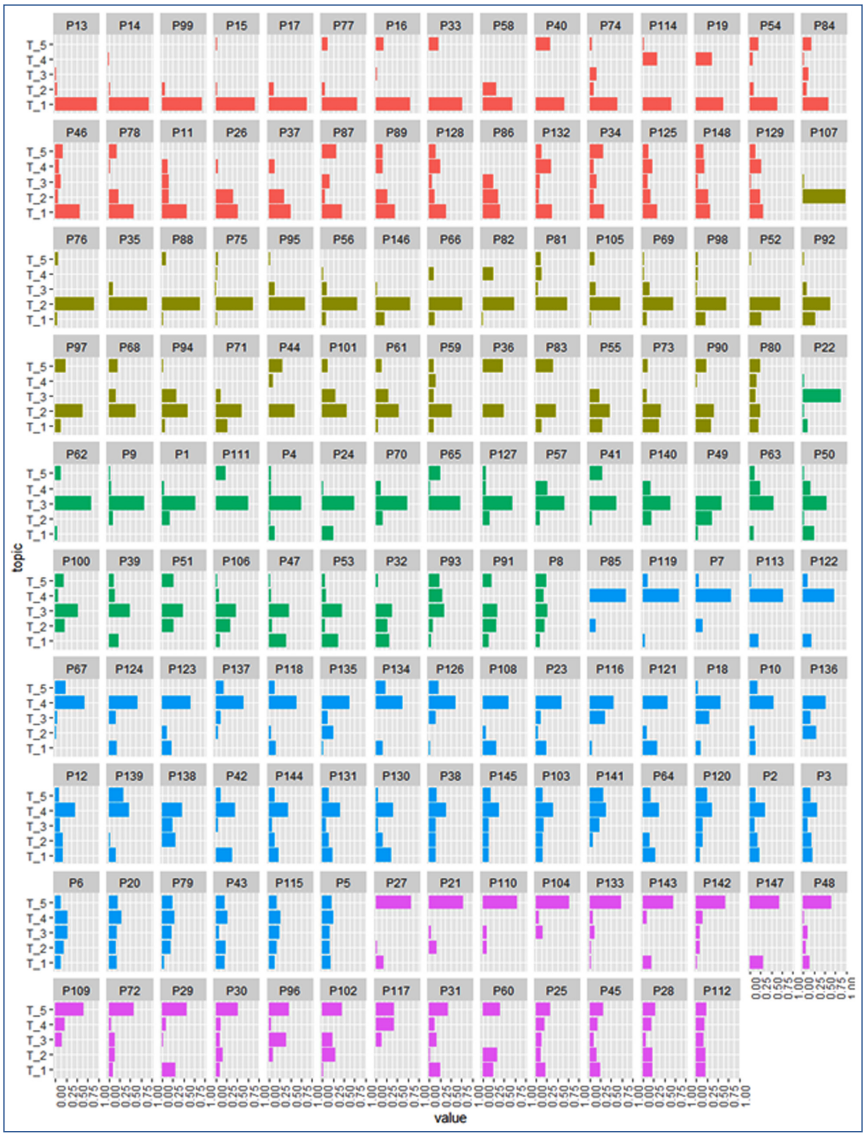

Figure 2 Loading Scores Across Texts.

groups. Consequently, the first-order free-rider problem is reduced by a coevolution of altruistic and cooperative social norms at the group level and the emergence of a selfish leader. Another high-loading example, Jaffe and Zaballa's (2010, P53) article, studies the second-order free-rider problem. While recognizing the community-wide benefits of punishing an individual who breaks an institution, the authors underscore the costs borne by the punishers. Using ABM, they examine social equilibria when the costs of punishment are shared across individuals and identify a bottom-up self-reinforcing system balanced by social norms and 'co-operative' punishment. Each of these papers emphasize the focal topics of *Topic Cluster #3*: the emergence and effects of institutions (e.g., cooperation, altruism, and punishment) in groups.

Topic Cluster #4: Natural Resources and Common-Pool Resources Management generally examines the roles of institutions in preventing the over-exploitation of natural and/or common-pool resources (P64, P6), including protected areas (P5), endangered species (P43), and cattle in grazing lands (P38). Campbell and colleagues (2000; P38) present simulation results for community destocking strategies which would lessen environmental costs of livestock production. Similarly, another predominant cluster text, Vallino (2014; P5), also engages in CPR modeling, examining the influence of externally-imposed institutions and endogenously-created institutions on the quality of environmental resources in protected areas. Okura and collaborators (2020; P108) analyze outcomes related to water scarcity, food security, and sustainable resource management as they pertain to individuals' water-use behaviors and differences in laws and institutions for water usage. These three papers exemplify the orientation of this cluster around the use of ABM to

model CPR dilemmas and natural resource management scenarios.

Topic Cluster #5: Predicting Human Behavior explores the human dimension as behavior emerges in simulated models. For example, scholars have simulated the behavior of individual people in order to understand and predict their aggregate behaviors (P109), micro-model to simulate interactions and individual behavior between agents (P38), and individual behavior of pedestrians in crowds (P45). Loscos and colleagues (2003, P45), a predominant cluster text, models real-time movements of 10,000 individuals walking under local laws and rules, for the purpose of reducing possible collisions in the crowd. Another highly-loaded text, O'Connell and O'Donell (2014, P48), uses a modeling approach which couples the natural and human systems to examine proactive approaches for moving citizens out of flood plains in the wake of future climate change. They argue that such models, which emphasize human behavior, are important to understanding the motivations, actions, and influence of citizens on institutions and vice versa. These papers each emphasize the human dynamics within the ABM and utilize modeling methods to examine individual and aggregated outcomes of the artificial systems.

EXAMINING TOPIC AND CITATION CLUSTER OVERLAP

As demonstrated in Table 4, topic and citation clusters were compared for overlap to explore possible intersections of theoretical- and topic-orientations. In doing so, we investigate whether siloing is evident between topical themes observed across paper abstracts and the theoretical orientations observed in the works they cite.

Topic Cluster #1: Decision-Making and System Outcomes, is represented by strong overlaps with both *Citation Cluster #2*: Ostrom (2005) *Understanding Institutional Diversity*, and *Citation Cluster #5:* Ostrom (1990) *Governing the Commons*. This link to Ostrom's work might be expected as the papers loading into this first cluster aim to model both the decision-making of individual agents as well as the institutions that constrain those decisions to examine system-based outcomes. Furthermore, papers in this topic cluster often identify this domain of modeling as 'social-ecological systems' — a perspective popularized by Ostrom at the end of her career. Additionally, papers loading into this topic cluster are commonly citing *Citation Cluster #4:* North (1990) *Institutions, Institutional Change, and Economic Performance*. While *Topic Cluster #1* leans heavily on Ostrom's work, the theoretical siloing of the cluster is not as apparent as in later clusters.

Topic Cluster #2: Societal Norms and Economic Institutions overlaps with both of Axlrod's citation clusters, *Citation Cluster #1*: Axelrod (1984) *The Evolution of Cooperation* and *Citation Cluster #3*: Axelrod (1986) "An Evolutionary Approach to Norms", as well as *Citation Cluster #4:* North's (1990) *Institutions, Institutional Change, and Economic Performance*. Given that the

		TOPIC CLUSTER				
		(1) DECISION-MAKING AND SYSTEM OUTCOMES	(2) SOCIETAL NORMS AND ECONOMIC INSTITUTIONS	(3) GROUP DYNAMICS AND EMERGENT INSTITUTIONS	(4) NATURAL RESOURCES AND COMMON-POOL RESOURCES MANAGEMENT	(5) PREDICTING HUMAN BEHAVIOR
Citation Cluster	(1) Axelrod (1984) *The Evolution of Cooperation*	1	10	11	3	1
	(2) Ostrom (2005) *Understanding Institutional Diversity*	6	2	1	4	1
	(3) Axelrod (1986) "An Evolutionary Approach to Norms"	2	7	4	1	3
	(4) North (1990) *Institutions, Institutional Change, and Economic Performance*	4	5	1	1	3
	(5) Ostrom (1990) *Governing the Commons*	7	3	3	12	6

Table 4 CIS-ABM Topic and Citation Cluster Overlaps.

Note: The numbers in the table denote how many articles belong to each combination of citation-topic clusters. Articles are sorted into clusters based on their highest load values for both citation clusters and topic clusters. Only 102 papers are represented in the table; this is because many papers do not clearly load into one topic as identified in Figure 2.

papers loading into Topic Cluster #2 examine various norms spurring the evolution or stabilization of economic and societal institutions, the theoretical orientation to past publications providing frames for understanding and evaluating norms, institutional evolution, and economic performance appears fitting. Furthermore, much like *Topic Cluster #1*, *Topic Cluster #2* leverages on multiple theoretical roots, suggesting less siloing than would be suggested by prior literature.

Topic Cluster #3: Group Dynamics and Emergent Institutions, more narrowly overlaps with Citation Cluster #1: Axelrod (1984) *The Evolution of Cooperation*, and to a much less extent, *Citation Cluster #3*: Axelrod (1986) *An Evolutionary Approach to Norms* and *Citation Cluster #5*: Ostrom (1990) *Governing the Commons*. Compared to other topic clusters, this overlap again aligns with siloing expectations, as there is a strong theoretical and topic overlap between the topical orientations of cooperation, altruism, and punishment in groups and Axelrod's discussion of cooperation in groups.

In *Topic Cluster #4: Natural Resources and Common-Pool Resources Management*, a narrower overlap is observed — this time with *Citation Cluster #5*: Ostrom (1990) *Governing the Commons*. This again might be expected and represent a topic-theoretical silo, as the papers that load into this cluster focus on modeling common-pool resource dilemmas and natural resource management — a topic that is directly addressed in Ostrom's work.

Finally, *Topic Cluster #5: Predicting Human Behavior*, is more theoretically diffuse, being linked to *Citation Cluster #3*: (Axelrod (1986) "An Evolutionary Approach to Norms"), *Citation Cluster #4*: North (1990) *Institutions, Institutional Change, and Economic Performance*, and *Citation Cluster #5*: Ostrom (1990) *Governing the Commons*. Given these papers' topical emphases on human decision-making dynamics and the use of ABM to examine individual and aggregated outcomes, the various citation cluster connections might be seen as orientations to different modeling approaches. As such, while the topic theme is consistent, *Topic Cluster #5: Predicting Human Behavior*, represents a theme which is more theoretically diffuse.

DISCUSSION OF FINDINGS

IDENTIFYING INTELLECTUAL SILOING, OR LACK THEREOF, IN CIS-ABM SCHOLARSHIP

Recently, researchers have retrospectively begun to aggregate a diffuse set of computationally-driven institutional analysis research constituting CIS, noting the potential for development of intellectual silos within such scholarship (Pieper et al. 2023; Siddiki and Frantz 2022). Through the identification of emergent citation clusters and topic clusters, we determine if intellectual siloing is observable in CIS research that leverages agent-based modeling. Ultimately, we find that, for CIS-ABM scholarship, such siloing is generally not occurring to the extent that existing literature predicts (e.g., Frantz and Siddiki 2022; Pieper et al. 2023), although the degree of siloing that does occur seems to vary depending on which clusters are examined.

As shown in Table 4, some topic clusters that emerge from our analysis (i.e., the columns of Table 4) are more theoretically siloed, that is, are more oriented around one citation cluster and its intellectual perspective, whereas others are more theoretically diffuse, orienting on multiple citation clusters. *Topic Cluster #3: Group Dynamics and Emergent Institutions* and *Topic Cluster #4: Natural Resources and Common-Pool Resources Management* both demonstrate a more exclusive, siloed overlap. *Topic Cluster #3*, with its works on cooperation and other emergent institutions in groups, exhibits a fairly unsurprising link to *Citation Cluster #1* which revolves around Axelrod's theoretical insights into the evolution of cooperation. The other four citation clusters were drawn on much less by works in *Topic Cluster #3*. *Topic Cluster #4* demonstrates a very similar pattern of interaction between topic and citation clusters whereby one key text, Ostrom's examination of institutions employed to govern the commons, emerges as a clear standout intellectual foundation. This topic cluster's reliance on that particular Ostrom publication is intuitive given the mutual interest in the role and ramifications of institutions in managing shared spaces and resources.

In addition, *Topic Cluster #1: Decision-Making and System Outcomes* and *Topic Cluster #2: Societal Norms and Economic Institutions* display a middling amount of siloing. Publications in *Topic Cluster #1* frequently overlapped with citation clusters revolving around Ostrom's work on institutional diversity (*Citation Cluster #2*) and institutions used to govern the commons (*Citation Cluster #5*), as well as North's examination of the effects of institutions on economic performance (*Citation Cluster #4*). The connections of *Topic Cluster #1* to these three citation clusters make sense given the publications' focus on the endogenous and exogenous institutions structuring decision-making and outcomes as a result of the equilibriums of such institutions. Interestingly, while *Topic Cluster #1* shows meaningful degrees of overlap with these three citation clusters, this topic cluster primarily orients around both of Ostrom's works. As such, publications with this topical focus appear likely to draw on the intellectual foundations that identify and unpack institutional diversity in the arrangements that structure social systems and shape individual and group decision-making.

Publications in *Topic Cluster #2* also clearly oriented around three citation clusters: Axelrod's evolution of cooperation (*Citation Cluster #1*) and norms more generally (*Citation Cluster #3*) as well as North's investigation of the economic ramifications of various institutional arrangements (*Citation Cluster #4*). Given this topic cluster's emergent interest in unpacking the institutions structuring societal and economic interactions, the existence of this more diffuse topic-citation cluster overlap seems reasonable as these works would understandably draw on a variety of past scholarship offering insight into the development and effect(s) of norms on larger societal groups. This topic cluster, again showing similarity to *Topic Cluster #1*, more strongly orients around the two clusters by the same author – in this case, both of Axelrod's works are more commonly drawn on by CIS-ABM research on group dynamics and emergent institutions.

Meanwhile, our analysis found *Topic Cluster #5: Predicting Human Behavior*, to exhibit much more diffuse overlap across multiple citation clusters compared to the previous four topic clusters. This topic cluster lacks a clear connection to one singular citation cluster as the first two topic clusters discussed and lacks a common author across its overlapping citation clusters as in the prior pair of topic clusters. Instead, *Topic Cluster #5* orients itself meaningfully across three citation clusters: Axelrod (*Citation Cluster #3*), North (*Citation Cluster #4*), and Ostrom (*Citation Cluster #5*). While each of these author's works offers guidance as to the expected behavior of individuals, they nonetheless represent theoretically distinct expectations, assumptions, and hypotheses. Thus, this topic cluster represents the most diffuse and least theoretically siloed topic cluster in our analysis.

PATTERNS OF INTELLECTUAL SILOING AND LINKS TO ABM

As explored in the previous subsection, intellectual siloing appears to occur with varying degrees within the examined CIS-ABM publications. While this observation is important, understanding how these clusters link to ABM research and inform computational institutional analysis is imperative for understanding where CIS scholarship is and advancing this inquiry through future work. Accordingly, in this final part of our discussion, we examine the various amounts of siloing we see in CIS-ABM research in relation to the scale of the social phenomena that scholars are modeling. To better identify the scale of social phenomena observed in our study's emergent topic clusters, we leverage the domain, context, and means structure identified by Miller and Page (2009) as fundamental to modeling complex social systems. While each collected CIS-ABM article has a *domain* grounding their model to a smaller, simpler version of the real world, a *context* engaging specific institutional concepts, and a *means* for operationalizing these concepts, we observe that different clusters of CIS-ABM literature identified in this study place greater emphasis on particular modeling aspects. Furthermore, this varied emphasis appears associated with the theoretical siloing of each topic cluster.

Domain-oriented topic clusters center around studying specific domains of research in which institutions are present and active in shaping behaviors — a common exercise in institutional analysis. At this macro-level, topics are linked to domains of research, often accompanied by distinct frameworks, conceptualizations, assumptions, and hypotheses. In our identified topic clusters, *Topic Cluster #4: Natural Resources and Common-Pool Resources Management* is a clear example of a domain-oriented-topic cluster, centered around a domain of interest, i.e., CPRs, within which institutions are studied. At this macro, domain-level orientation, Ostrom's (1990) *Governing the Commons* can be seen as the predominant theoretical lens, advanced by a commons scholar, to make sense of natural resource use and CPRs. As such, her work offers a theoretical framework, which identifies expectations and hypotheses for inquiry into the management of these resources broadly.

Within the CIS-ABM papers that fall into *Topic Cluster #4* represent approaches where computational institutional analysis is employed to gain a better understanding of the institutional design phenomena discussed by Ostrom through simulated investigations of hypotheses that may not or cannot be examined in the real world. Collectively, works in this domain-oriented topic cluster are somewhat narrowly siloed, with CIS-ABM techniques being engaged to simulate applications of a conceptual framework regarding CPR governance and test hypotheses advanced from this theoretical foundation. Given the narrower emergent focus of Topic Cluster #4 and the similarly tailored scope of its primary citation cluster, the intellectual siloing that we see occurring between these clusters makes sense. Researchers modeling the institutions and institutional dynamics of natural resources and CPR management heavily relied on an intellectual orientation that is reflective of the topical interests of these computational simulations. A clear example of this connection is Schill and colleagues' paper (2016, P116), which leverages Ostrom's work as a theoretical root of their hypotheses around CPR dilemmas and cooperation in sustainable resource use. They then utilize ABM to examine important variation across knowledge sharing in the group, ultimately finding that cooperation through face-to-face dialogue does not necessarily produce optimal CPR outcomes, as the accuracy of the information and the willingness to share it are also

key factors. Thus, in this paper, the authors engage in specific domain of research, sustainable CPR management, and aptly leverage the theoretical framework to understand the institutional arrangements of CPRs governance in constructing and implementing a computational model of such institutions and their ramifications.

Context-oriented topic clusters, meanwhile, study variations in particular conceptual aspects of institutional arrangements pertaining to the design and/or the form of these institutions (e.g., emergence of formal or informal institutions, and collective action). At this meso-level, the focus is often on group-level outcomes. In our analysis, a more moderate amount of siloing was found with regard to context-oriented publications, particularly, *Topic Cluster #2: Societal Norms and Economic Institutions*, with its focus on group equilibria, commonly involving simulations studying entire groups, policy system domains, and/or large-scale, societal-level or market-level institutions. Examining the overlap between topic clusters and citation clusters again helps us understand the amount of siloing observed, as the papers in this topic cluster are broadly studying emergent institutions (leveraging Axelrod's works) to better understand stability and outcomes in the broader group being modeled (leveraging North's work). As such, a specific domain of research appears less central to the works in *Topic Cluster #*2, in comparison to *Topic Cluster #*4, as these publications model institutional dynamics across societal, economic, and political settings. The absence of a particular domain thus makes the lower degree of intellectual siloing exhibited by this topic cluster less surprising as the approaches taken to simulate this array of social phenomena would not be expected to orient toward one theoretical frame. Frantz and colleagues' paper (2014, P68), for example, exemplifies such an approach, as it explores norm formation and diffusion as a means to replicate economic transitions. Thus, the focus of the paper is on the emergence of institutions and the establishment of group-level equilibriums rather than the effects of domain-specific institutional arrangements. Furthermore, the paper does not focus more narrowly on the means of model parameterization, an orientation of CIS-ABM work discussed next.

Finally, means-oriented topic clusters focus on innovating and improving the operationalization of institutional concepts in ABM, or the means by which the individual parameters of the ABM is modeled. One of our emergent topic clusters, *Topic Cluster #5: Predicting Human Behavior,* centers primarily around the measurement and operationalization of institutional concepts, predominantly revolving around methodological development and refinement for improved modeling of institutional concepts (e.g., norm compliance, rule adaptation). Thus, in contrast to the earlier orientations that looked at entire institutionalized domains or specific contextual institutional dimensions and dynamics, this means-oriented cluster focuses more intensively on better parameterizing institutions for modeling purposes and more diffusely draws on various theoretical traditions to inform these measurement and simulation activities.

For instance, Burgess and colleagues' paper (2020, P109) falls into *Citation Cluster #5,* which centers on Ostrom's examination of CPR governance, as they engage in improved modeling of human behavior in fisheries as actors adapt to ecosystem changes. Razo's paper (2021; P31) falls into *Citation Cluster #*4, which exhibits a common interest in the ramifications of institutions, particularly on economic performance, as the author focuses on parameterizing individual investment behavior and the outcomes of Crony Capitalism. Afshar and colleagues' paper (2021; P61) falls into *Citation Cluster #3*, with its focus on emergent institutions, as they focus on simulating the influence of one's belief system and other social sanctions on an individual's decision-making. While these publications all develop and refine parameters for use in modeling behavior and the institutions that constrain or enable it, they do so by engaging different theoretical lenses as called for by the institutional concept in which they are interested (e.g., socio-ecological, economic, and psychological). Thus, in contrast to domain-oriented and context-oriented clusters, where CIS-ABM scholarship appears to draw more narrowly on a singular theoretical framework or even on a single author's theoretical perspective, means-oriented clusters engage more diverse intellectual orientations to develop and enhance CIS-ABM measurements and techniques.

Existing literature suggests institutional analysis, particularly analysis with computational means, is intellectually siloed within particular theoretical orientations (Pieper et al. 2023; Siddiki & Frantz 2022). In our analysis, we do not see consistent amounts of theoretical siloing across the emergent topic clusters we identify. In the topic cluster we identify, for example, domain-specific works exhibit more theoretical reliance on a narrower scope of existing research, such as works on the governance of common-pool resources drawing heavily on Ostrom's works. Meanwhile, for research that engages and investigates more abstracted concepts such as norm emergence, the intellectual siloing is weaker in our results, suggesting the need for a greater breadth and scope of theories to engage these social phenomena. Thus, our findings suggest that CIS-ABM scholars may engage more siloed theoretical orientations in examinations of more tailored topical investigations. In these instances, then, the presence of a theoretical silo may complement the specificity of researchers' questions or the specific domain of inquiry.

Ultimately, the study of institutions and their ramifications is key to support multiple crucial social phenomena such as resource governance, or more broadly, collective action. ABM is identified as a valuable tool for performing institutional analysis though how this tool is utilized can vary though scholars have noted the potential for siloed engagement. Therefore, through this work, we identify the presence and patterns of intellectual siloing in CIS-ABM scholarship and note that narrower theoretical orientations might be apt for inquiries focusing on the domain-oriented topics. Alternatively, more diffuse theoretical orientations that lack siloing could be more appropriate for research seeking to explore context- or means-oriented topics. While discussions of clear potential benefits and drawbacks of such trends in intellectual siloing are beyond the scope of this work, it would seem wise for scholars preparing to engage in CIS-ABM research to consider the scope and specificity of the questions and concepts they aim to investigate as they look to existing literature for theory and guidance.

CONCLUSION

Collectively, through our review of CIS-ABM studies, we see Computational Institutional Science emerge from the convergence of existing scholarship and knowledge regarding institutional analysis, social science, and computational methods. It draws heavily from a diverse set of disciplinary (e.g., political science, sociology, economics, computer science) and theoretical origins. Furthermore, from this disciplinary and theoretical intersection, CIS research explores different social phenomena (e.g., cooperation, compliance) in a variety of topical domains (e.g., ecosystem management, economic markets) while leveraging multiple computational tools. Scholars have often discussed CIS scholarship within intellectual silos (Pieper et al. 2023; Siddiki and Frantz 2022) due to two reasons: (1) its diverse application, as highlighted throughout this study; and (2) the retrospective identification of CIS as a coherent research agenda. In this paper, we track and explore this intellectual siloing is CIS-ABM research, observing multiple theoretical and topical fronts, as well as their overlaps. To do this, we leverage topic modeling and network analysis, thereby allowing this paper to not only serve as an examination of theoretical and empirical knowledge, but also as a methodological means of sense-making of CIS research.

We find that intellectual siloing is not readily observed as current CIS literature would suggest (Pieper et al. 2023; Siddiki and Frantz 2022). Furthermore, the amount of intellectual siloing appears to vary across research topics with respect to the institutional scale (i.e., the ABM's domain, context, or means) emphasized in each paper in our sample (Miller and Page, 2009). We observe the following pattern: domain-oriented topics represent more theoretical siloing, as they leverage a more defined and singular framework, expectation, or hypothesis being tested within a specific research domain; context-oriented topics represent a middling theoretical siloing, as they leverage theoretical insights to group-level equilibriums and broader societal expectations; and means-oriented topics represent less theoretical siloing, as they leverage broad theoretical frameworks from diffuse disciplines to better parameterize ABM models.

While the identification of less siloing than previously suggested and patterns to such siloing is important to understanding the emergence of CIS research, a few limitations to this research are identified. First, as suggested throughout this paper, the retrospective identification of research as CIS includes a diffuse set of scholarships. As such, we have captured this scholarship with a broad set of search terms as well as a manual review of papers, yet we acknowledge the full scope of papers that one might define as 'CIS' might not be represented. As the boundaries of CIS become clearer, the inclusion of research for review will become more apparent. Our desire in this study is to begin to identify these boundaries and make sense of what was captured inside. Second, we view this research as a means of sense-making as well as an opportunity to bring together diffuse strands of research. While the modeling used allows for statistical clustering, the sense-making of each cluster is informed by our own backgrounds. Our hope is that our work starts a conversation to better understand and integrate these diverse strands of research. Finally, we focus narrowly here on the use of ABM in CIS. We acknowledge that ABM does not encompass all computational, institutional analysis, but we had to set the bounds of our study. We encourage future and complementary work that examines the overlaps of CIS research using different approaches.

While the results of this study are interesting in and of in and of themselves, they call into question how diverse researchers in CIS-ABM engage with the literature as a whole. As stated above, each ABM model includes a domain, context, and means. While a domain-oriented research project focuses on testing hypotheses linked to a narrow theoretical root, it still models components of context and means. Thus, despite the more narrow theoretical focus expected for the project, a broad understanding of ABM-CIS is still needed to include innovations in the means of parameterization and modeling. Such innovations might be occurring not only across multiple journals and conference

proceedings, but also across multiple disciplines and their publication outlets. Thus, this work not only offers insights into the siloing or diffuseness of the CIS-ABM literature, but suggests that when examining innovation across domain, context, and means, scholars should look to divergent scholastic traditions for insights regarding different institutional scales.

NOTE

1 If the first author of a citation is observed in the authors of the manuscript, these citations were not counted. This was done to reduce any inflation in our analysis due to self-citations.

ADDITIONAL FILE

The additional file for this article can be found as follows:

- **Appendix.** Appendix Table 1–Appendix Table 6. DOI: https://doi.org/10.5334/ijc.1335.s1

ACKNOWLEDGEMENTS

The authors would like to thank the journal's editor and anonymous reviewers for their comments that greatly helped improve the manuscript.

COMPETING INTERESTS

The authors have no competing interests to declare.

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TO CITE THIS ARTICLE:
Oesterling, N., Ambrose, G., & Kim, J. (2024). Understanding the Emergence of Computational Institutional Science: A Review of Computational Modeling of Institutions and Institutional Dynamics. *International Journal of the Commons*, 18(1), pp. 425–443. DOI: https://doi.org/10.5334/ijc.1335

Submitted: 27 August 2023 **Accepted:** 06 May 2024 **Published:** 12 June 2024