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The organic seed innovation system: Unpacking the who, where, and how of niche formation

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Abstract

The challenges facing agricultural systems – biodiversity loss, climate change, and corporate consolidation of food production, to name a few – demand transitions to more environmentally and socially sustainable agricultural systems. To investigate the processes supporting these transitions, the three chapters of this dissertation combine theories and methods from environmental policy and governance, innovation systems, and social networks to analyze the empirical case of the organic seed system – the actors, institutions, and socio-technical innovations involved in breeding, producing, processing, selling, and regulating seeds suitable for organic agricultural production.

Chapter 1 focuses on the so-called "organic seed loophole" in the United States' organic standards, whereby growers can use conventional seed if organic seed is not commercially available, and investigates the effects of this policy on organic growers' seed sourcing choices. By modeling survey data on US organic growers' seed sourcing practices from three cross-sections over the last 15 years, we find evidence for both the intended effects of the policy (helping organic growers who face seed sourcing barriers to maintain organic status) and for unintended effects, i.e. allowing growers to source non-organic seed even though organic seed is commercially available. Chapter 2 maps the spatial boundaries of the organic seed network to test the propositions of the Global Innovation Systems framework. Using survey data of organic seed stakeholders collected between 2020-2022, we operationalize the organic seed innovation system as a multi-functional network. This includes various knowledge and market-based relationships between organic seed producers, researchers, companies, and non-profit organizations. We analyze the network using inferential network analysis methods and find that the framework explains its structure well, as the organic seed network is built up by regionally embedded knowledge creation and product valuation systems. Finally, Chapter 3 analyzes the organic seed innovation system as an emergent system and investigates the role of different types of actors in explaining its formation. Using network analysis and the same data from Chapter 2, we test the resource-based theory of system building and the institutional logics of the multi-actor perspective. We find that the organic seed network is shaped primarily by "partner mode" structures, suggesting that cooperative and complementary resource-sharing relationships drive system formation. Furthermore, our models show how actor involvement varies along functional lines, where non-profit actors are generally more active in pre-competitive activities like knowledge creation, while for-profit actors are more active in market-based functions like value chain creation.

The findings of this dissertation research help guide policy recommendations for developing the organic seed system, a niche innovation system that plays a pivotal role in the transition towards sustainable agriculture. Furthermore, the research contributes to the field of innovation systems by empirically testing and extending networking-building theory using inferential network analyses. This approach contributes to a more generalizable understanding about the who, where, and how of innovation system formation, ultimately deepening our understanding of managing sustainability transitions.

Contents

Introduction

The challenges facing agricultural systems – biodiversity loss, climate change, and corporate consolidation of food production, to name a few – demand transitions to more environmentally and socially sustainable agricultural systems (Hebinck et al. 2021). Supporting sustainability transitions, however, is no easy task. While the decision to adopt a new technology or change behavior is made at the individual level (Buttel, Jr, and Larson 1990; Rogers 2003), individuals are shaped by the broader innovation system in which they are nested (Laureans Klerkx, Mierlo, and Leeuwis 2012). An innovation system is the complex of interactions between actors and institutions that nurture and diffuse new technologies or practices based on several interdependent processes, such as policy-making, knowledge creation, and market formation (Bergek et al. 2008). The interplay between individual behaviors and system level processes is at the core of successful innovation and transitions. Which processes to foster for successful transitions, at what scale, and by whom are core questions in the niche management and innovation system literature (Binz and Truffer 2017; Musiolik et al. 2020; Smith and Raven 2012; Suurs 2009).

Across three chapters, this dissertation addresses questions about sustainability transitions at both the individual and system levels using the case of organic seed. Among the inputs necessary for supporting a sustainable agricultural system, seeds are one of the most foundational. While the dominant seed breeding approach in countries like the United States is based on high-input, low-diversity and highly centralized conventional agricultural practices (Lammerts van Bueren et al. 2018), several alternatives (so-called "niches") have developed to support a more sustainable system. This work focuses on the organic agriculture niche, in which seed production systems are typically low-input and high diversity with polycentric management (Colley 2022; Rohe et al. 2022; Shelton and Tracy 2015). The focus on organic seeds was inspired by the Organic Seed Alliance's (OSA) *State of Organic Seed Reports* (Dillon and Hubbard 2011; Hubbard and Zystro 2016). OSA's research conceives of organic seed as part of a broader system – not just breeding and agronomy, but also policy support, funding mobilization, community building, and small business development. This framing mirrors the innovation systems approach, where environmental challenges require system-level assessments that connect and transcend disciplines.

The focus of Chapter 1 is on the organic standards in the United States, specifically, the so-called "seed loophole" whereby growers can use conventional seed if organic seed is not commercially available and still retain their organic status. We investigate whether this loophole helps reduce organic growers' seed sourcing burden, as the policy intends, or enables them to free-ride by using conventional seed despite commercial availability. Drawing on organic grower survey data from three cross-sections over the last 15 years, we use beta regression to model individual growers' seed sourcing behavior. The results of the regression suggest that the loophole is a double-edged sword in that it both helps growers facing seed sourcing barriers, and allows some growers to take advantage of the flexibility by reducing their efforts in sourcing organic seed. The chapter concludes with several policy recommendations, which align with the 2022 *State of Organic Seed Report* (Hubbard, Zystro, and Wood 2022). Beyond, it opens up a wider discussion about competing motivations and identities in sustainability transitions to be considered in future research.

Chapters 2 and 3 broaden the scope of study from the individual-level to the system-level. Both of these chapters draw on innovation system theory, combined with policy network and social network literature, to quantify and explain the relationships within the organic seed innovation system as a network. We use survey data of over 200 organic seed stakeholders within and outside the United States, collected between 2020-2022, to create a multi-functional innovation system network comprising 645 actors and 1206 connections between them. These connections operationalize knowledge and market-based relationships between organic seed producers, researchers, companies, and non-profit organizations.

In detail, Chapter 2 focuses on explaining the spatial structure of the US organic seed network, testing the propositions defined by the Global Innovation Systems framework (Binz and Truffer 2017). Using n-clan compositional analysis and Exponential Random Graph Modeling, we find support for the framework's proposition that types of innovation and production valuation are two key conditions predicting the innovation network's spatial structure. In line with these conditions, we find that the organic seed system has a "spatially sticky" network structure, in that both knowledge creation and product valuation are territorially embedded in different regions of the country. But even in a regionally sticky innovation system, we find that national-scale actors (e.g. the US national germplasm repository) serve a prominent role in connecting regional networks. These results highlight both the importance of tailoring policies to the place-specific needs of regional organic seed systems, and the importance of coordination from higher-scale actors.

Chapter 3 investigates the processes and actor composition of the organic seed innovation system. Again using Exponential Random Graph Modeling on the organic seed networks, we test two theories in parallel: resource-based theory of system building (Musiolik et al. 2020) and the institutional logics of the multi-actor perspective (Avelino and Wittmayer 2016). In line with the expectations from the resource-based theory, we find that the organic seed network is shaped primarily by "partner mode" structures, suggesting that cooperative and complementary resource-sharing relationships drive system formation. Second, our results align with the proposition that actors' "institutional logics" affect their activity in certain network functions. For example, non-profit actors are generally more active in pre-competitive activities like knowledge creation, while for-profit actors are more active in market-based functions like value chain creation. The one exception is governmental actors, who are more active in market-based functions, pointing to their innovation-nurturing role when niches are not yet competitive.

Together, the chapters in this dissertation make the following contributions. Chapter 1 analyzes the effects of the "seed loophole" in the United States organic standard, and makes several policy recommendations for achieving the intended effects of the policy while curbing free-riding behavior on the part of organic growers. Chapters 2 and 3 contribute to the field of sustainability transitions by empirically testing and extending innovation system theory using inferential network analysis. By employing Exponential Random Graph Models, these chapters not only describe the organic seed network, but also investigate its structural determinants to help build a more generalizable understanding of innovation system formation. This work combines theory and methods from the two otherwise disparate bodies of knowledge on innovation systems and policy networks, to help deepen our understanding of managing and supporting sustainability transitions.

Chapter 1

The double-edged sword of flexible environmental policy: The case of the seed loophole in certified organic production

1. Introduction

Environmental policies play a critical role in addressing the complex suite of sustainability challenges facing agricultural systems – biodiversity loss, climate change, corporate consolidation and loss of food sovereignty, to name a few (Hebinck et al. 2021; Piñeiro et al. 2020). Effective environmental policy has to walk the line between being stringent enough to improve environmental outcomes, while also flexible enough so that the policies don't backfire (Barreiro-Hurle et al. 2023; Sunstein 2017). Overly stringent policies may cause industries to relocate or find methods for creative compliance to avoid the burden of change (Bartel and Barclay 2011). Yet, too flexible of policies can be taken advantage of by free-riders, enabling industries to shirk environmental responsibilities while still gaining the benefits of (perceived) compliance (Prakash and Potoski 2007). In this paper we ask: *Do flexible environmental standards spare firms undue burden or enable free-riders?*

To answer this question we study a flexible voluntary environmental policy: the so-called "seed loophole" of organic agricultural certification in the United States (US). Organic standards require growers to comply with a wide range of practices and sourcing rules that support soil health and biodiversity, and reduce environmental impact. Using certified organic seed is one of the sourcing requirements, however, the policy permits exceptions if the variety is not "commercially available" (7 CFR § 205.204). This exception, mirrored in organic policies around the world, gives flexibility to growers with their seed sourcing to ideally limit the burden when organic seeds are unavailable.

This paper analyzes organic growers' reliance on the organic seed exception using three cross-sectional surveys over the last 15 years. We measure organic growers' use of conventional seed (i.e. their reliance on the loophole), as well as attributes like their experiences with seed sourcing barriers, perceptions about organic seed, and details of their farm operation. Using these data, we model the relationship between conventional seed use and grower attributes to test hypotheses about the sparing and/or enabling effect of the flexible policy.

We find evidence that the flexibility of the organic seed loophole is both supporting growers who need it, as well as enabling free-riding by organic farmers who follow an approach that is more practical than principled. The use of conventional seed is associated with growers who experience the highest barriers to sourcing organic seed, meaning that the policy does help reduce the burden on growers who cannot find suitable seed in organic form. At the same time, the policy also allows a certain profile of farmers to avoid organic seed use. Farmers of this profile appear to be those that represent the “conventionalization” of organic agriculture – larger, less diverse farm operations managed by growers who don’t value organic seed as important for the integrity of organic production.

These results track with the idea that actors have different motivations for compliance with environmental policy (Bartel and Barclay 2011) and that policy design needs to account for this nuance and be responsive to the changing dynamics of the targeted sector (Piñeiro et al. 2020). Though policy design research tends to treat firms as purely rational actors (Prakash and Potoski 2007), farmers especially have different motivations and embrace business models that balance economic and environmental values (Brown et al. 2021; Thompson, Reimer, and Prokopy 2015). These come through as two identities of organic, practical and principled (Darnhofer et al. 2010), which affect the ways that growers engage with the policy. Not only can reckoning with these identities help strike a better balance within the policy, it also opens up a broader conversation about the different kinds of sustainability that the policy wants to support. For organic seed, supporting different kinds of sustainability would mean developing a mix of policies that support traditional expansion of organic seed availability through stricter enforcement of the policy, as well as alternative initiatives that support more principled, grassroots organic seed programs.

The paper will be structured as follows. In Section 2 we review existing literature on the tradeoffs of different environmental policy tools and describe the organic agriculture policy setting. We conclude the section with an articulation of our hypotheses. In Section 3 we describe our research methods, including our case based on the US, survey data collection process, and modeling approach. Next we present our results in Section 4, where we first describe organic growers and their reliance on the organic seed loophole over the last 15 years. We then explain our model results and highlight the different production models of "practical" and "principled" organic farmers. Last, we discuss the results and their implications in Section 5 and conclude in Section 6.

2. Background

2.1 Environmental policy flexibility

Environmental policy has to strike a balance between stringency and flexibility. Stringent environmental policies often take a command and control approach, where firms are required to meet specific criteria such as defined contributions, reduction targets, or technology standards (Barreiro-Hurle et al. 2023; Pettersson and Söderholm 2014). These types of regulatory measures reduce uncertainty in the achievement of environmental outcomes so long as enforcement is in place (Piñeiro et al. 2020). However, stringency has its drawbacks. The increase of regulation may reduce competitiveness of firms (Brännlund and Lundgren 2009), counteract voluntary behavior (Barreiro-Hurle et al. 2023), prompt relocation to an area with more lenient policies (Cole 2004), or generate resistance/creative compliance (Bartel and Barclay 2011).

Flexible environmental policies, on the other hand, tend to use tools that incentivize firms to improve environmental outcomes (Gunningham and Sinclair 1999; Piñeiro et al. 2020), and at times permit exceptions/derogations if the regulation is overly burdensome (Romero-Castro, López-Cabarcos, and Piñeiro-Chousa 2022). The benefits of flexible policies include reduced tension between firms and government, as well as room for innovation to ultimately improve environmental outcomes (Ambec et al. 2013). The drawback of flexible policy tools, however, is that adherence needs to be monitored to avoid free-riding (Prakash and Potoski 2007), and because participation may be low, there is less certainty around the environmental benefits (Stuart, Benveniste, and Harris 2014). Furthermore, vague criteria for exceptions/derogations like the use of "best available technology" gives wide latitude to firms' discretion (Romero-Castro, López-Cabarcos, and Piñeiro-Chousa 2022).

In this paper we are interested in environmental policy that provides flexibility in the form of exceptions. For example, the European Union industrial emissions directive mandates firms to reduce emissions using "best available technology," but grants derogations if the costs of complying (as calculated by the firm) are too high (Romero-Castro, López-Cabarcos, and Piñeiro-Chousa 2022; Söderholm et al. 2022). As a second example, regulation of manure discharge by animal feeding operations in the US has several exceptions to regulation based on nutrient management plans (Rosov, Mallin, and Cahoon 2020). Who takes advantage of these exceptions is an open question, prompting our research question: Do flexible environmental standards spare firms from undue burden or enable free-riders?

2.2 Organic agricultural standards

2.2.1 Flexibility of organic certification

Organic certification is a voluntary program that agricultural producers and food processors opt into, which requires a range of practices and sourcing rules that reduce the environmental impact of agricultural production. Participants are then monitored according to the certification standards, making these high-cost clubs that use stringent voluntary standards to gain participants premiums (Prakash and Potoski 2007). However, the certification standards are generally accompanied by listed exceptions for using non-organic products. These exceptions are proposed to reduce excessive burdens and barriers facing growers and processors (Board 2006) in an otherwise stringent and often challenging certification process (Carter et al. 2022; Flaten et al. 2010).

One such exception in the organic label is related to seed sourcing. Organic standards generally require organic growers to use organic seed. However, so-called "loopholes" are often put into place, where organic growers are allowed to use conventional seed if organic seed is not commercially available (Endres et al. 2022; Liveseed 2021; Padel et al. 2021). This kind of exception is common in organic standards around the world, for example the United States' National Organic Program[1], United Kingdom's Soil Association and the European Union's Organic Standard[2], and the East Africa Organic Standard[3].

In the United States, "the goal [of the exception] is to promote the continued growth and improvement in organic seed production and subsequent usage by organic growers, without hurting or putting undo [sic] burdens on growers" (Board 2008). The intention is that this exception can excuse farmers who experience challenges, particularly as the organic seed market develops (Dillon and Hubbard 2011; Hubbard and Zystro 2016). While there is evidence that the seed system is growing through increased public research spending and the development of new organic varieties (Hubbard, Zystro, and Wood 2022), there is still widespread uncertainty as to how the seed loophole is used by organic growers.

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[1] "...an equivalent organically produced variety is not commercially available" (USDA NOP 7 CFR § 205.204).

[2] "When there are no organic or in-conversion seeds or vegetative propagating material of a suitable variety available you may use non-organic" (UK Soil Association via (EC) 834/2007 Art. 22(2)(b) (EC) 889/2008 Art. 45(1)(b))

[3] "If organic seeds, seedlings and planting materials are not commercially available, then conventional, chemically untreated seed, seedlings and planting material may be used. Only if these are not commercially available may chemically treated seeds, seedlings and planting materials be used. The operator shall demonstrate the apparent need for such use." (Kilimohai Organic, East African Organic Product Standards)

2.2.2 Different models of organic farming

To develop an understanding of how organic growers are using the seed loophole, we first recognize that farmers (and firms generally) have different motivations (Bartel and Barclay 2011). Many policy design studies tend to treat firms as purely rational actors. As Prakash and Potoski describe it, "firms choose to join a voluntary club (and produce the environmental externalities it requires) in response to the costs of externality production and the returns from affiliating with the voluntary club brand" (2007, 287). But in reality, firm-level decisions are made by actors with varying risk tolerances, entrepreneurial initiatives, and environmental values and strategies. This is especially true for agricultural settings, where securing economic returns exists on balance with other values and operational attributes (Floress et al. 2017; Prokopy et al. 2019).

Farmers make decisions based on a gradient of values ranging from "farm-as-business" to "environmental stewardship," though the two are not mutually exclusive (Daloğlu et al. 2014; Thompson, Reimer, and Prokopy 2015). Additionally, operational attributes such as farm size can influence the willingness and ability to innovate. In some cases large operations may be the ones that have the resources to take on risk and experiment with new practices (Daloğlu et al. 2014; Feder and Umali 1993), but in other cases it may hinder their willingness to try something new at a large scale, especially if there is no visible economic return (Buttel, Jr, and Larson 1990; Napier, Robinson, and Tucker 2000).

Variation in grower motivations is especially prominent in organic agriculture. Organic farming originated as a grassroots movement, centered around holistic environmental and social farming principles (Youngberg and DeMuth 2013). This vision of sustainability emphasizes soil health, biodiversity, social justice, and community food systems as a contrast to the industrialized model of conventional farms (Coleman 2001; Youngberg and DeMuth 2013). But when codified into practice as certified organic standards, a model of "conventionalized" organic emerged. In this conventionalization, growers participate in organic practices (as defined by the standard) but not organic principles (as defined by the movement's broader social-environmental ethos), mainly to gain the price premium (Darnhofer et al. 2010; Guthman 2014).

The division between principled and practical organic farmers has created tension around the identity of organic farming (Coleman 2001; Sehlen 2007). This tension has come to bear throughout the process of setting and revising the certification standards, such as the bi-annual discussion of the National Organic Standards Board, where exceptions are reviewed and updated (DuPuis and Gillon 2009). Indeed, these discussions reflect a wider conversation about the vision of what organic is and the appropriate path to achieve it. Though the division between principled and practical organic farmers does not fully represent the diversity of farmer profiles involved in organic (Darnhofer et al. 2010; Guthman 2014), they help us typify different ways that growers may be engaging with the organic standard and its flexibility.

2.3. Hypotheses

We use the case of the organic agricultural standard to understand whether flexible environmental policies like the seed loophole spare farmers from undue burden or enable free-riders. We propose two sets of hypotheses.

The first set of hypotheses test whether environmental policy flexibility reduces excessive burden on firms. Organic farming is certainly challenging (Sahm et al. 2013), and barriers to complying with the standard are high, especially in the early phases of the certification's establishment. As such, we expect to see evidence that growers who are relying on the seed loophole (i.e. planting conventional seed) are those who experience the greatest barriers to accessing organic seed. Furthermore, we expect that as the organic seed market develops over time, fewer growers use conventional seed.

> H1a. Conventional seed use will be highest among growers experiencing greater organic seed sourcing barriers
>
> H1b. Conventional seed use will decline over time

The second set of hypotheses test whether environmental policy flexibility enables some farmers to take advantage of the policy's leniency (Prakash and Potoski 2007; Stuart, Benveniste, and Harris 2014). In the case of the seed loophole, though guidance for growers and certifiers has tried to operationalize the commercial availability exception (Board 2018), there is still opportunity for shirking. We propose that those particularly inclined to take advantage of the policy's leniency are farmers fitting the practical, more conventionalized profile, given that they have little principled motivation to adopt organic seed. In this case, we expect to see evidence that growers relying on the seed loophole are those who align with that profile – farmers who place low value on organic seeds' role in organic integrity, and have operations that resemble conventional farms: large acreage and low crop diversity.

> H2a. Conventional seed use will be highest among growers with who place low value on organic seeds' contribution to organic integrity
>
> H2b. Conventional seed use will be highest on large farms
>
> H2c. Conventional seed use will be highest on low-diversity farms

3. Methods

3.1 Case: USDA National Organic Program and organic seed

In this paper we focus on the case of the US Department of Agriculture (USDA) certified organic label. The organic movement in the US began prominently organizing in the 1970s, and it is through their collective action that the Organic Foods Production Act was passed as part of the 1990 Farm Bill and ultimately ratified in 2002 (Youngberg and DeMuth 2013). In the arrangement, the USDA National Organic Program (NOP) determines the standards, though they are advised by the National Organic Standards Board (NOSB) – a panel of industry representatives that meets regularly to continuously discuss exceptions and general guidance with input from the public.

The general idea of certified organic crop production is that growers use only biological inputs (e.g. no pesticides or genetically modified seeds) to create an agro-ecosystem with healthy soil, diverse crop rotations, and minimal environmental impact (NOP 2015). From start to finish of the certified organic supply chain, inputs should be organic to protect the integrity of the label, including seeds. In practical terms, organic seeds are those that are cultivated under certified organic conditions, meaning that using organic seed contributes to environmental outcomes by having more acreage managed under organic practices. The principle of organic seed, however, extends even further. Organic seeds ought to support genetic and crop diversity maintenance, be adapted to organic growing conditions, and suitable for regional environments (Hubbard, Zystro, and Wood 2022; Rohe et al. 2022). Furthermore, organic breeding is often collaborative, where seed sovereignty and social needs are included as project considerations (Colley 2022; Dawson et al. 2011). Altogether, organic seed is a foundational part of organic production, especially for more principled organic growers (Hubbard, Zystro, and Wood 2022).

There are exceptions to several of the organic requirements, as mentioned in Section 2.2.1. Of focus in this paper is that USDA NOP growers are allowed to use conventional seed if “an equivalent organically produced variety is not commercially available” (7 CFR § 205.204). Third-party organic certifiers are responsible for evaluating organic growers' compliance with the organic standard, and whether or not a farm qualifies for the organic seed exemption is at their discretion. Now that more than twenty years have passed since the ratification of the NOP, we draw on data to understand trends in seed use and the attributes of growers that have been unable to source organic seed. Such an assessment can help policymakers rethink the organic seed policy as the US organic standard enters into its third decade.

3.2 Data: Organic grower surveys

This research combines three cross-sectional surveys of organic seed producers in the United States. These data were collected between 2009-2011, 2014-2016, and 2019-2021, which we will refer to as the 2010, 2015, and 2020 time periods. The nation-wide organic grower survey, orchestrated by the national non-profit organization Organic Seed Alliance, covers four topics: farm profile, use of organic seed, barriers to organic seed and sourcing, and attitudes towards organic seed.

In each data collection period, grower surveys were distributed using one or both of the following methods: a random sample from the USDA NOP INTEGRITY database and a convenience sample from an open-access web survey. Responses from both the combined random and convenience samples resulted in a total of 899 responses in 2010, 1,162 responses in 2015, and 760 responses in 2020 that had identifiable regions and crops. The points on the map in Figure 1.1 represent the distribution of our survey respondents.

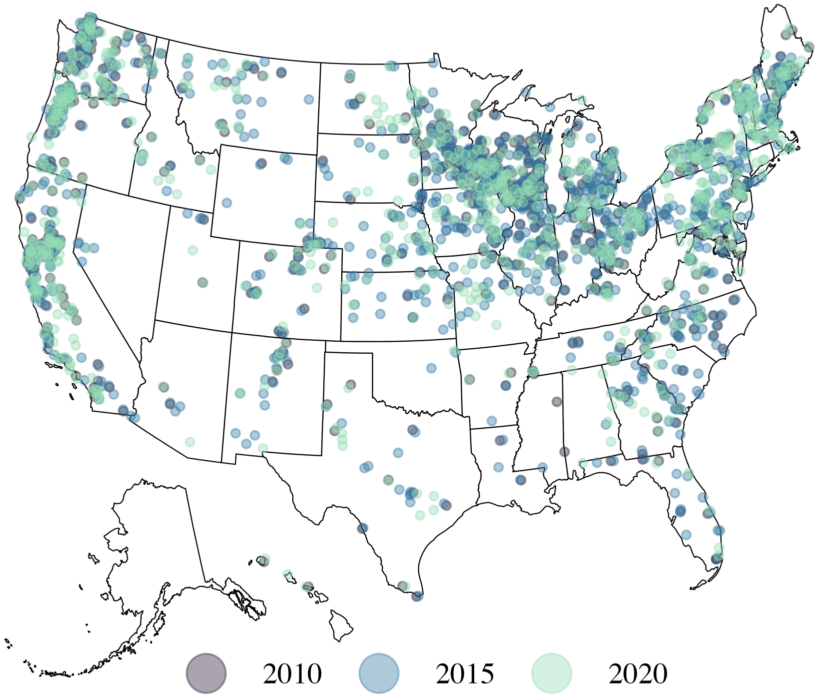

Figure 1.1: Map of survey responses (points) across the United States over three time periods: 2010 (purple), 2015 (blue), 2020 (green).

We cannot associate a response rate with our convenience sampling, but the response rates for the random samples were 25% in 2015 and 22.5% in 2020 (convenience sampling only in 2010). Of these responses, 545 (2010), 799 (2015) and 408 (2020) were complete and therefore usable in our analysis.

3.3 Analysis

3.3.1 Variables

Descriptions of the variables used in our model are described in Table 1.1. The key dependent variable in our model is *acreage planted to conventional seed.* The survey asks respondents: “Last year, what approximate percentage of total acreage of [vegetable/forage/field crops] was planted with certified organic seed?” The response to this question is a continuous variable between 0 and 100, which was converted into a proportion. Then we subtracted this value from one to represent the proportion of acreage planted to conventional seed.

Our analysis includes eight independent variables for predicting adoption. The first five variables are relevant to our first hypotheses. These include four variables describing *barriers* to sourcing organic seed. Growers were asked, “Over the last three years, how much were each of the following a factor in your decision NOT to purchase organic seed?”. The top reasons include: Variety is not available as organic, lack of desirable genetic traits, insufficient quantity of seed, and processor/buyer requires or supplies varieties that are not available in organic form. Responses were Likert-scale ratings from “Not a factor” (1) to “Significant factor” (4). Additionally, the *survey year* variable captures how the organic seed market has changed over time.

The next three variables are relevant to our second hypotheses. Organic growers’ principled *value of organic seed* is based on respondents’ agreement with the statement: “Organic seed is important in maintaining the integrity of organic food production.” Agreement ranged from “Strongly disagree” (1) to “Strongly agree” (5). *Farm size*, measured as acreage ranging from 1-17,000 acres, is a representation of scale and farm resources. And *crop diversity* is the number of crop categories growers produce, which include field, vegetable, and forage crops.

Last, we include four variables in our model as controls – variables we expect to influence adoption but are not of theoretical interest to this paper. These include the amount of *seed sourced via seed saving or trading*, represented as the percentage of seeds that farmers report sourcing from either their own farm or from other farmers, ranging between 0 and 100 percent. *Certifiers request organic seed use* is the growers' reported experience with certifiers' regulatory enforcement. Growers were asked the yes-no question: "Over the last three years has your certifier requested that you take greater steps to source organic seed?". Last, we include the *region* in which the farmer is located and the *main crop* of that grower based on their percent acreage planted to that crop, to account for variation in the development and availability of organic seed in these different subsystems.

3.3.2 Modeling approach

We use a beta regression model to estimate the relationships between organic growers' use of conventional seed and their attributes. The beta distribution is best suited for our model given that the dependent variable of conventional seed use is bounded by 0 and 1, representing the proportion of acreage. Prior to fitting the model, we transformed the data in two ways. First, the acreage proportion data was truncated by 0.001 so that observations fall within (but not equal to) the 0-1 boundaries of a beta distribution (Rue, Martino, and Chopin 2009). Second, all independent variables are mean-centered and scaled for easier interpretation of coefficients. This way, the values of the coefficients represent the proportion increase in conventional seed used based on a unit change from the mean of the variable.

We ran our analysis using the INLA package (Rue, Martino, and Chopin 2009) available in R Statistical software (Team 2023). INLA uses an Integrated Nested Laplace Approx-

Table 1.1: Organic seed grower survey questions, key variables, and hypotheses

Data description	Hypothesis	Variable name	Data type
Dependent variable			
Last year, what approximate percentage of total acreage of [crop] was planted with conventional seed?		Acreage planted to conventional seed	Proportion (0-1)
Independent variables			
Over the last three years, how much were each of the following a factor in your decision NOT to purchase organic seed?			
Specific variety not available as organic seed	H1a	Barrier: Organic availability	Likert scale (1-4)
Insufficient quantity of seed	H1a	Barrier: Insufficient quantity	Likert scale (1-4)
Lack of desirable genetic traits	H1a	Barrier: Undesirable traits	Likert scale (1-4)
Processor/buyer requires or supplies varieties that are not available	H1a	Barrier: Buyer requirements	Likert scale (1-4)
Survey year	H1b	Survey year	Categorical (2010, 2015, 2020)
Please indicate your level of agreement with the statement: Organic seed is important in maintaining the integrity of organic food production	H2a	Values organic seed	Likert scale (1-5)
Total acreage	H2b	Farm size (acres)	Numeric (0-17,000)
Crop diversity	H2c	Crop diversity	Numeric (1-3)
Control variables			
Has your certifier requested that you take greater steps to source organic seed?		Certifiers request organic seed use	Binary (0-1)
Sources seed from self or other farmers		Seed saved or traded (%)	Percent (0-100)
Main crop		Crop	Categorical (Field, Forage, Vegetable)
Region		Region	Categorical (N. Central, West, Northeast, South)

imation – a deterministic Bayesian method for estimating its models. Code for analysis is available at github.com/liza-wood/organicseed_adoption. We compare several models and provide measures of model fit in Appendix A.

4. Results

4.1 State of organic seed

Across the three time periods of our survey (2010, 2015, 2020), the mean values and their standard deviations are reported in Table 1.2. Conventional seed use has been moderately low since the inception of the organic certification. The mean proportion of organic crop acreage planted to conventional seed decreased from 43% to 32% between 2010 and 2015, then to 29% in 2020, with high standard deviations. These numbers suggest that most farmers are planting at least some organic seed, though those planting 100% organic seed represented only 21%, 27%, and 26% of growers in 2010, 2015, and 2020, respectively.

The most significant barrier that growers report as limiting their organic seed sourcing is that a specific variety is not available in organic form, which is ranked greater than 3 (between moderate and significant factor) in all three survey periods. The barriers of insufficient quantity and desirable genetic traits both score an average of 2.6 (between low and moderate factor) in 2010, and those scores decrease by 2020. Buyer requirements are the least significant barrier to sourcing organic seed, but it does remain a consistent, low ranked factor over time.

Across the three survey periods, growers' perceived value of organic seed as important to organic integrity has remained consistently high. In the 2010 survey, the average agreement score with the statement that organic seed is important to the integrity of organic production was 4 (somewhat important), which increased to 4.3 in 2015 and 2020. The operational profile of organic growers matches the profile of agricultural production more generally, in that farm sizes are increasing (Sumner 2014). The average farm size over the three survey periods was 180, 275, and 346 acres. This increase is most pronounced in field and forage crops. Further, the number of crop categories planted by growers has been declining, with an average of 1.7 crop types in 2010 down to an average of 1.3 in 2020.

The relationship between certifiers and organic growers has shifted over the years, as it appears that organic certifiers are becoming less strict. When non-compliant growers (i.e. growers not already using 100% organic seed) were asked whether or not their certifier had requested they increase their organic seed use, 61% responded yes in 2010, decreasing to 56% in 2015 and 46% in 2020. This decline suggests that certifiers are becoming less insistent to ensure that growers are taking measures to source organic seed. Further, reliance on non-commercial seed sources, via seed saving and seed exchange, has decreased from 23% and 24% in 2010 and 2015 to 15% in 2020.

4.2 Sparing those facing barriers

In this section we present model results related to our first set of hypotheses, which propose that environmental policies add flexibility in order to reduce excessive burden on organic producers. We present the mean coefficient estimates and credible intervals of our model results in Figure 1.2. Full model results are available in Appendix A.

Of the four organic seed sourcing barriers facing organic growers, three have a significant positive relationship with planting conventional seed. The barriers related to organic seed variety availability, lacking desirable genetic traits, and limitations in choice via buyer

Table 1.2: Mean values and standard deviations (reported in pathenses) for key variables from the organic grower surveys

Questions	2010	2015	2020
Proportion of acreage planted to conventional seed	0.43 (0.38)	0.32 (0.36)	0.29 (0.36)
Barrier: Organic availability	3.55 (0.95)	3.05 (1.22)	3.19 (1.15)
Barrier: Insufficient quantity of organic seed	2.62 (1.29)	2.22 (1.23)	2 (1.16)
Barrier: Lack of desirable genetic traits	2.63 (1.33)	2.15 (1.26)	2.31 (1.27)
Barrier: Buyer requirements	1.87 (1.26)	1.63 (1.13)	1.9 (1.25)
Values organic seed	4.03 (1.07)	4.29 (0.96)	4.32 (0.89)
Farm size (acres)	181.05 (342.15)	275.16 (645.05)	346.98 (999.54)
Vegetable Crop Acreage	27.58 (90.34)	62.79 (427.81)	12.3 (47.81)
Field Crop Acreage	178.21 (347.15)	259.32 (490.56)	351.51 (812.27)
Forage Crop Acreage	98.96 (124.74)	122.03 (197.63)	172.11 (548.85)
Crop diversity	1.66 (0.64)	1.5 (0.6)	1.25 (0.56)
Certifiers request organic seed use	0.61	0.56	0.46
Seed saved or traded (%)	22.54 (29.95)	23.67 (31.69)	14.63 (24.05)
Number of respondents	545	799	408

requirements have effect sizes of 0.17, 0.12, and 0.12, respectively. In other words, for each unit higher that a grower ranks the barrier of organic variety availability, for example, the proportion of acreage planted to convention seed increases by a mean estimate of 0.17 (17%). This estimate is based on all other variables being held constant at their mean or baseline. So for example, these effects are calculated based on having an average farm size, number of crops, and value rating of organic seed, among other variables. The barrier related to insufficient quantity of an organic variety was not significantly related to conventional seed use.

Regarding survey year, we find that conventional seed use significantly decreased over time. In 2015, the coefficient estimate is -0.18, suggesting that compared to the baseline data in 2010, growers are planting 18% less of their acreage to conventional seed. Likewise in 2020, growers are planting 32% less of their acreage to conventional seed. These results support our first hypotheses: Conventional seed use will be highest among growers experiencing more significant organic seed sourcing barriers (H1a) and conven-

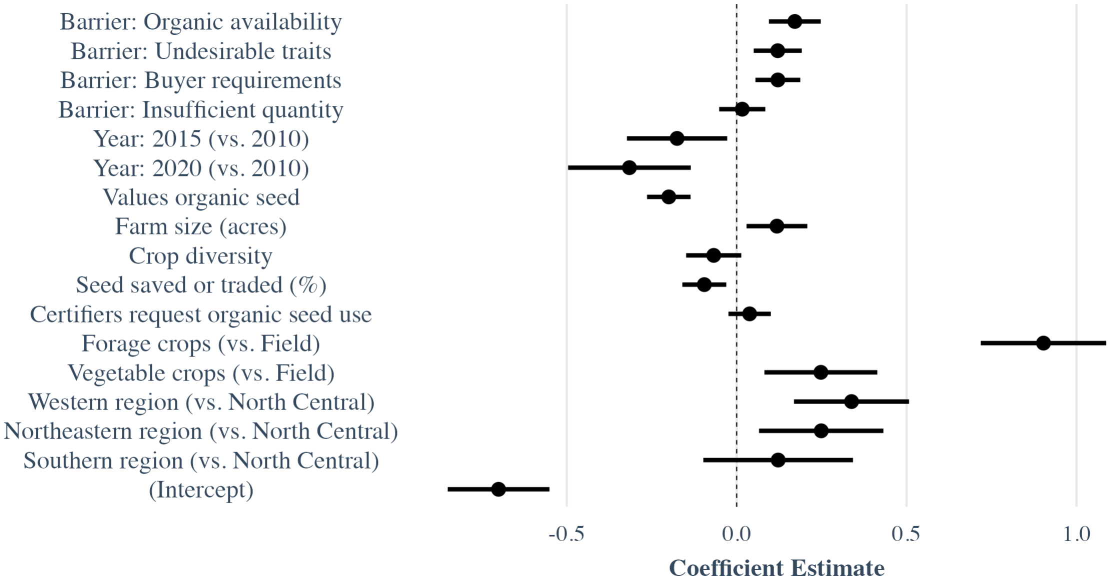

Figure 1.2: Coefficient estimates and credible intervals for the beta regression modeling the proportion of total acreage planted with conventional seed.

tional seed use will decline over time (H1b). Together, they suggest that the flexibility of the organic seed policy is being used by those with the highest seed sourcing burden, and as the organic seed market develops over time, growers rely less on the seed policy exception.

4.3 Enabling less-principled farmers

Next we address our second set of hypotheses, which propose that policy flexibility enables some farmers to take advantage of the policy's leniency. A grower's rating of organic seed's value has a significant negative relationship with planting conventional seed. Our model estimates an effect size of -0.2, meaning that for every unit higher that a grower ranks the value of organic seed, the acreage planted to conventional seed decreases by 20%. All else held equal – so for example farmers who experience the same barriers and have the same farm sizes – the principled belief that organic seed is important to the integrity of organic farming has a considerable effect on how much acreage a grower plants to conventional versus organic seed.

Regarding operational characteristics, farm size has a significant positive relationship with planting conventional seed. For every unit larger a farm is, growers plant 12% more of their acreage to conventional seed. Crop diversity has a negative relationship with planting conventional seed, with an effect size of -0.07, but credible intervals that span between -0.14 and 0.01, making this result not significant.

These results support all three of our second hypotheses: Conventional seed use will be highest among those with who place low value on organic seeds' contribution to organic integrity (H2a), as well as operations that resemble a more conventional model, such as large farm size (H2b) and low-diversity (H2c). These results suggest that certain farmers' profiles – notably those that align with a "practical" organic grower – rely more on the organic seed policy exception than more "principled" organic growers.

The crop and regional controls in our model highlight considerable variation in adoption based on these different organic subsystems. Forage crop growers plant an estimated 90% more of their acreage to conventional seed compared to field crop growers, while vegetable crop growers plant an estimated 25% more. Regionally, compared to the baseline of the North Central region, growers from both the West and the Northeast regions plant significantly more of their acreage to conventional seed, with coefficient estimates of 0.34 and 0.25, respectively. The estimate for the Southern region is also higher than the baseline (0.12), though the credible intervals of this estimate cross over zero.

We take results related to our second set of hypotheses and visualize the differences between two typified farmer profiles: practical and principled. A practical farmer profile is defined by a low value of organic seed (25th percentile), large farm size (75th percentile), and low crop diversity (25th percentile). A principled farmer profile is the opposite, characterized by a high value of organic seed (75th percentile), small farms (25th percentile), and high crop diversity (75th percentile). We calculate these profiles for each region in the United States and use the example of vegetable crops, with all other variables fixed at their median value. Using these two profiles we estimate their predicted acreage planted to conventional seed using our model.

Figure 1.3 visualizes model predictions of conventional seed use by hypothetical vegetable growers from these two farmer profiles across regions in the United States. From the predicted values we see a consistent difference between the two farm profiles: practical farmers rely more on the seed policy loophole, planting between 19-51% more acreage to conventional seed than principled farmers in 2010, 25-85% in 2015, and 5-23% in 2020. We run these same predictions for field and forage crops (available in Appendix A) and observe equal or even greater differences between the two farm profiles over the three time periods.

5. Discussion

5.1 Flexibility in the organic standard is double-edged

We find support for both our hypotheses related to the role of environmental policy flexibility in the organic standard. The seed loophole is being used by those with the highest seed sourcing burden, as well as those with more "practical" farm profiles. These results suggest that the flexibility of the organic policy is both sparing firms from undue burden *and* enabling free-riders. Simply put, the standard's flexibility is a double-edged sword, as pointed out by plant breeder John Navazio in an interview about the seed loophole (Roseboro 2018).

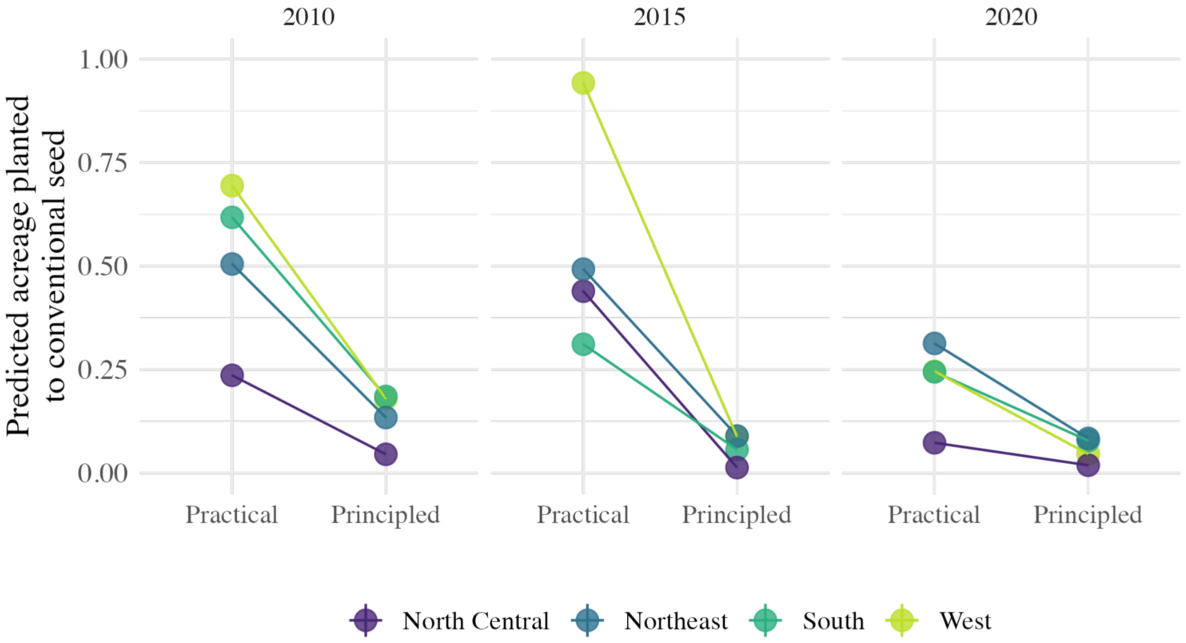

Figure 1.3: Predicted estimates of conventional seed use for vegetable crop growers of two farmer profiles. Estimates are made for each region of the US, represented by the different colored points (see legend). Lines connecting points help visualize the difference in predicted adoption between practical and principled growers.

These results from the organic seed case make three contributions to the conversation about environmental policy flexibility and design. First, our results point to the need for a more nuanced discussion around how to design and adjust policies to account for different motivations (Bartel and Barclay 2011). Because firms, farmers, and people generally respond to environmental policy flexibility (and stringency) differently, tools need to be designed to account for this (Piñeiro et al. 2020).

Second, policy design should be iterative in order to respond to the changing dynamics of a sector. While the organic movement was pioneered by principled growers, the system has changed (Youngberg and DeMuth 2013). The number and size of organic operations have increased considerably over the past 20 years, and along with it there has been a trend towards more conventionalized models of organic production (Darnhofer et al. 2010; Guthman 2014). This change calls attention to the necessary re-evaluation of the organic seed loophole, as what may have been initially enabling organic integrity at the start of the standard may now be limiting it.

Third, environmental policies are closely linked to a broader policy ecosystem, particularly innovation policy. The intent of the organic seed loophole's flexibility was established to allow the organic seed market time to develop (Board 2008), revealing its interdependence with a wider set of innovation policies for organic seed research, development, and expansion. Recognizing these interdependencies can help build stronger policy mixes that support sustainability transitions (Rogge and Reichardt 2016).

5.2 Reckoning with identities in sustainability transitions

While finding the right policy design and level of flexibility is central to improving environmental outcomes (Gunningham and Sinclair 1999), there also needs to be a recognition that different motivations represent competing identities and normative views of sustainability (Jain et al. 2023; Meadowcroft 2009). Policies play an important role in empowering certain views on sustainability and ultimately steering the direction of a sustainability transition towards either "conforming to" or "transforming" the system (Smith and Raven 2012). Our results highlight this tension in the organic movement, between practical and principled farmers, and open up discussion about how these identities are shaping the development of the organic system.

On one hand, organic growers with more practical identities embrace a more conformist view of sustainability transitions by modeling themselves after conventional operations (Smith and Raven 2012). For example, the Cal-Organic farm has grown from a quarter of an acre of organic production to one of the nation's largest organic vegetable providers, in part due to mergers with conventional operations and an industrial supply chain connection with Whole Foods (`https://calorganicfarms.com/our-story/`). Likewise, Bayer CropScience, one of the largest agri-chemical and seed companies in the world, has recently announced its entry into the organic seed market (Bayer 2021). This conforming model is what motivates several sustainability initiatives such as electric vehicles and offshore wind (Kern et al. 2015; Köhler, Turnheim, and Hodson 2020), where the focus is on altering the mainstream approach through technology substitution.

On the other hand, organic growers with more principled identities tend to represent a transformative view of sustainability transitions by refusing to replicate the systems they seek to replace (Duncan and Pascucci 2017; Smith and Raven 2012). For example, Bee Heaven Farm in Florida produces mixed vegetables for direct sales on five acres, and grow out seed for use on their operation. Farms like these are asserting their ethic through initiatives like the "Real Organic" label, that oppose what is perceived as the industrial co-opting of the organic standard (`www.realorganicproject.org`). This is true for some parts of the organic movement (Youngberg and DeMuth 2013) but also movements like the open source software initiative (Jain et al. 2023), community energy initiatives (Seyfang et al. 2014), and Hackerlabs (Smith et al. 2017). More than just technological substitution, these movements are associated with social innovations to replace dominant institutions (Avelino et al. 2019).

By and large, environmental policies are designed in accordance with the former, conformist approach. As a result, the focus is largely on getting incentive structures right so that pro-environmental behavior and technological innovation can flourish and scale (Prakash and Potoski 2007). Yet, our results point to the coexistence of both conforming and transforming visions of sustainability transitions through the clear difference in seed sourcing behavior by practical and principled farmer profiles. Based on these findings, we propose that designing a well-balanced environmental policy needs to reckon with these multiple, sometimes competing identities.

6. Conclusion

In this paper we use the case of the organic agricultural standard to understand whether flexible environmental policies spare farmers from undue burden or enable free-riding. Our focus is specifically on the seed loophole, which gives organic growers discretion to use conventional seed when organic seed is not "commercially available." We draw on three cross-sectional surveys collected over the last 15 years to understand how organic growers are using the loophole. Our results suggest that the standards' flexibility both supports growers who face the highest seed sourcing barriers, and enables free-riding by organic farmers who follow a more "conventionalized" approach. These results highlight the need for policy design that accounts for different motivations, is iterative in its understanding of how growers take advantage of the flexibility over time, and is reflexive to the types of sustainability transitions that the policy aims to support.

With the US organic standard entering into its third decade, insights from this paper can support policymakers in their organic seed policy design. We conclude with recommendations related to organic seed innovation and the organic seed loophole, which need to recognize and promote both the practical and principled models of the organic label. These recommendations are inspired by the Organic Seed Alliance's *Policy Platform for Seed* (Alliance 2022). Regarding innovation, policy should continue to support organic seed innovation through continued funding for research and organic variety development, as well as seed producer education and expansion. This seed innovation support should include traditional plant breeding research pipelines by companies, as well as grassroots initiatives like participatory breeding, the open-source seed initiative, and resources directed to pre-competitive agricultural needs such as climate change adaptation and minor crop development.

Regarding the seed loophole, the organic seed sourcing requirement in the organic standard should be strengthened. Organic growers should be required to demonstrate improvement in organic seed sourcing to their certifier, which has already been proposed by the NOSB (Board 2018). Beyond the existing guidance, growers over certain sales or size thresholds should also be required to conduct variety trials and/or contract seed producers to grow out desired varieties using organic standards. Paired with these efforts, the US should look to the European Union's model for registering organic seed varieties in centralized databases, which is part of the effort to phase out their organic seed exceptions by 2036 (Liveseed 2021). These improvements can help certifiers more easily identify non-compliance, which if paired with increased enforcement ability, can help hold free-riders to account.

Ultimately, strengthening the organic seed requirement should lead to an eventual closing of the seed loophole to support organic seed innovation and maintain the integrity of the organic label. These policy changes, however, should be developed in a way that recognizes the different identities of organic growers. In this way, the appropriate mix of environmental and innovation policies are designed with an eye for supporting diverse sustainability transition pathways.

Chapter 2

Mapping the spatial boundaries of the organic seed niche: Testing the Global Innovation System framework with social network analysis

1. Introduction

Innovation systems (IS) are a complex network of actors and institutions that interact to develop and diffuse technological and/or social innovations (Bergek et al. 2008). The field of IS has led to insights that support policy recommendations for fostering innovation for sustainable development, particularly from "niche" phases.

Yet, studies on innovation have long been grappling with the challenge of defining meaningful boundaries around these systems (Binz et al. 2020; Coenen, Benneworth, and Truffer 2012). System boundaries affect how we understand an innovation's development and success (Wieczorek et al. 2015), and therefore identifying meaningful boundaries is a first step towards a generalizable understanding of how and why systems evolve (Binz, Truffer, and Coenen 2014).

Given the importance of boundary-setting, this paper asks: *What determines the spatial boundaries of an innovation system?* We answer this question by drawing on the Global Innovation Systems (GIS) framework (Binz and Truffer 2017). The GIS framework outlines two dimensions that help predict IS spatial structure: innovation "mode" and how the product is valued. Along these two dimensions, an IS is operationalized into knowledge and valuation resource subsystems to test the theory's structural propositions. This paper aims to test and deepen the framework's theoretical underpinnings using a novel empirical case and methodological approach.

We use the case of the organic seed system, a niche technological (and social) innovation system where a variety of actors interact to support development and use of organic seed. In accordance with the dimensions of the GIS framework, this case combines a "doing-using-interactive" innovation mode and customized product valuation, theoretically positioning it as a "spatially sticky" innovation system. Spatially sticky systems are those where knowledge and market related resources are territorially embedded, making closely knit regional networks (Binz and Truffer 2017). We test this proposition of the GIS framework using network data collected from surveys of organic seed innovation system actors and analyze them using two social network analytical approaches: n-clan analysis and Exponential Random Graph Models.

Our results point to three main findings. First, the organic seed networks show strong regional embeddedness in the structure of both the knowledge and valuation resource subsystems, supporting the GIS proposition that innovation mode and product valuation are strong predictors of IS spatial boundaries (Binz and Truffer 2017). Second, our findings suggest that higher-scale actors encourage vertical structural coupling by acting as coordinating bridges between lower-scale actors (MacKinnon, Afewerki, and Karlsen 2022; Rohe 2020). And third, the knowledge and market based subsystems are horizontally coupled, where activity in one subsystem positively affects activity in the other (Tsouri, Hanson, and Normann 2021).

Altogether, these results confirm the expectations outlined by the GIS and add nuance to the understanding of how actors link to one another within and across spatial scales. Particularly, we show how even in a regionally sticky innovation system, national and international-scale actors still serve a prominent role in providing resources among regional networks. Furthermore, actors tend to be active in more than one resource subsystem, pointing to actors' ability to support multiple functions and stimulate resource spillovers. The contributions made in this paper are part of a broader effort to add theoretical depth to innovation systems scholarship by developing a generalizable understanding of system boundaries (Kern 2015; Markard, Hekkert, and Jacobsson 2015), and to expand the field's methodological toolkit (Köhler et al. 2019).

The paper will be structured as follows. In Section 2 we review existing literature on the role of space in IS studies and outline the components and dimensions of the GIS framework. We then describe the organic seed system and its placement in the typology, and conclude the section with an articulation of our hypotheses. In Section 3 we describe our research methods, including our sampling approach and survey distribution, network construction, and social network analysis methods. Next we describe our results in Section 4, divided into descriptions of spatial composition and inferences based on our network model. Last, we discuss the results and their implications in Section 5 and conclude in Section 6.

2. Background

2.1 The spatial turn of innovation systems

The innovation systems (IS) perspective proposes that transitions are driven by a broad range of networked interactions for developing, promoting, and diffusing new technological and/or behavioral innovations (Bergek et al. 2008). Where to draw the boundary around those networked interactions has long been of interest, resulting in several IS subfields, including national, regional, technological and sectoral innovation systems (Carlsson et al. 2002; Freeman 1995). While these subfields impose boundaries around an IS, geography of transitions scholars propose a spatial turn in order to think more critically about boundary-setting (Binz et al. 2020; Coenen, Benneworth, and Truffer 2012; Rohe 2020). Proponents of this spatial turn argue that previous delineations often fail to take into account heterogeneity at regional levels (Rohe and Mattes 2022), variation in actors' roles depending on the scale at which they operate (Wieczorek et al. 2015), and spillover from global scales (Binz, Truffer, and Coenen 2014).

Scholarship in the geography of transitions focuses on the effects of space and scale. Innovation systems are not homogenous across space, but rather, there can be a great deal of regional, place-based variation across broader innovation systems (Rohe and Mattes 2022). This heterogeneity comes from innovation system functions that can be spatially "sticky," meaning they are closely linked to space (Rohe 2020; Rohe and Chlebna 2021). Beyond regional heterogeneity, actors operate at different scales (e.g. local producers, regional organizations, national governments, multinational companies). The scale at which an actor operates influences both their mandate and the resources they have to carry out that mandate (Bergek et al. 2015). For example, regional actors can be important bridges between local actors, as their mandate is to connect different geographies across shared issues (Vantaggiato et al. 2023). And indeed, actor roles and scales can interact, as institutional logics of different actors may shift as their scale of operation increases (Lamers et al. 2017). Furthermore, resources can spillover, both between regions (Kreft et al. 2023) and at higher scales through active national or international-scale actors (Wieczorek et al. 2015).

To capture the effects of space and scale on innovation system boundaries, Binz and Truffer (2017) develop a Global Innovation Systems (GIS) framework to explain the spatial distribution of IS resources. This framework proposes that an IS be operationalized as subsystems based on its different resource-building relationships (Binz, Truffer, and Coenen 2016; Musiolik, Markard, and Hekkert 2012). These subsystems are then expected to match certain spatial characteristics based on two conditions: innovation mode and type of product valuation. In the following sections we describe the components for operationalizing an innovation system network and the conditions that define the GIS spatial typology.

2.2 Components of an innovation system network

Innovation systems are often defined in terms of functions and structures (Wieczorek and Hekkert 2012). Functionally, innovation systems rely on a series of processes that support its development: entrepreneurial experimentation, knowledge creation, collective influence on the direction of search, market formation, resource mobilization, and creation of legitimacy (Bergek et al. 2008; Hekkert et al. 2007). These IS functions have been synthesized to represent "system resources" provided by networks, summarized as knowledge, investment/capital, market, and legitimation resources (Binz, Truffer, and Coenen 2016). Structurally, a diverse set of actors, institutions and their interactions relative to a technology are the scaffolding of an innovation system, responsible for supporting these functions and building system resources (Jacobsson and Johnson 2000; Musiolik and Markard 2011). These two features of an IS, function and structure, map onto components of the GIS as a network: *innovation subsystems* and *structural coupling* (Binz and Truffer 2017).

The functions of an IS can be operationalized as innovation subsystems (Binz and Truffer 2017). These innovation subsystems are the networked relationships that arise to carry out a particular function, such as developing and exchanging knowledge, sharing resources, and creating legitimacy (Rohe 2020). There have been several efforts to represent innovation subsystems based on specific functional relationships. For instance, knowledge creation is often operationalized by co-authorship (Binz, Truffer, and Coenen 2014), joint project participation (Alphen et al. 2010; Hermans, Stuiver, et al. 2013), or co-patents (Belderbos et al. 2014). Other functions are more rarely quantified, such as legitimacy (Heiberg, Binz, and Truffer 2020; Rohe and Chlebna 2021) and resource mobilization (Giurca and Metz 2018). These networks of functional relationships, which we will henceforth refer to as “resource-based innovation subsystems,” provide a basis for operationalizing the relationships that form the networks of an IS.

The connections that define the structure of an innovation subsystem are made by actor-to-actor relationships. For each of these actors we can identify certain spatial attributes: geographic space and/or operational scale. How these actors create connections across space is conceptualized as “structural coupling” (Binz and Truffer 2017). Under the initial GIS framework, structural coupling is understood as the linkages within or between scales of a subsystem that enable mobilizing of innovation system resources. As this framework has developed, the structural coupling concept has been extended to include different types: vertical and horizontal (Rohe 2020).

Vertical coupling is a linkage between actors at different geographical and/or operational scales. For example, actors from two different regions may connect to help build legitimacy for an innovation (MacKinnon, Afewerki, and Karlsen 2022), or a regional-scale actor may connect with a national-scale actor to obtain resources like knowledge or funding (Rohe 2020). The GIS emphasizes this latter type of connection, where higher-scale actors "with global reach" (Binz and Truffer 2017, 1287) support lower-scale network actors through resource provision (Bergek et al. 2015). However, the exact understanding of how scale affects coupling within and/or between scales of a subsystem still requires some clarity (Binz, Truffer, and Coenen 2014; Tsouri, Hanson, and Normann 2021).

Horizontal coupling is a linkage between resource subsystems, whereby the resources developed in one network, such as knowledge development, spillover into other networks to provide resources like legitimation and market access (Rohe 2020). For example, one study of Norwegian offshore wind power finds that spillovers between resource subsystems depend on the type and scales of knowledge creation activities, whereby higher-scale (international) R&D collaboration improves access to international markets (Tsouri, Hanson, and Normann 2021). Together, different forms of coupling link actors within and between spaces and scales, as well as within and between resource subsystems, all of which create the spatial architecture of the innovation system.

2.3 Typology of IS spatial configurations

Once innovation systems have been operationalized based on their resource-based subsystems and structural couplings, the GIS framework outlines dimensions that help predict when different spatial configurations occur (Binz and Truffer 2017). Those two dimensions are the innovation mode, related to the knowledge resource subsystem, and product valuation, related to the valuation resource subsystem.

Innovation mode describes the types of knowledge and learning that are required for the innovation to develop and thrive. The GIS defines two end-points of an innovation mode gradient, ranging from "science and technology" (ST) to "doing-using-interacting" (DUI) innovation (Jensen et al. 2007). These innovation modes align well with other conceptions of learning across disciplines, such as codified vs. tacit knowledge (Binz, Truffer, and Coenen 2014) and technical vs. social and experiential learning (Lubell, Niles, and Hoffman 2014). In the former cases, ST knowledge is formalized, typically in science-based industries, and can be transferred easily across contexts in forms like patents and designs (Jensen et al. 2007). In the latter case, DUI knowledge is created through practice and application, and is rooted in social and experiential knowledge transfer (Gertler 2003). Regarding space, the GIS proposes that innovations in the ST mode are less spatially bound given knowledge's codification and transferability, while DUI innovations are more connected to specific spaces and contexts. The IS resource relevant to this dimension is the knowledge resource, where relationships for creating and diffusing knowledge form the knowledge subsystem (Binz and Truffer 2020).

The product valuation dimension describes how a product is valued by users (Binz and Truffer 2017). The GIS framework identifies a gradient of valuation systems from standardized to customized (Jeannerat and Kebir 2016). Standardized valuation is where "consumption and legitimacy are stabilized around clearly identified goods, services, and brands" (Binz and Truffer 2017, 1289). Products and services with customized valuation, in contrast, build legitimacy and market-following based on the specialization of their products to particular contexts (Jeannerat and Kebir 2016). This valuation gradient aligns with different organizational types of value chains, which contrast hierarchical, formalized and industrialized value chains from democratic and territorially embedded value chains (Duncan and Pascucci 2017; Gaitán-Cremaschi et al. 2018). Regarding space, the GIS proposes that goods with standardized valuation can supply different regional contexts without customization, and are therefore easily transferable, where the same cannot be said for customized products. The innovation system resources relevant to this dimension are the resource mobilization, market formation, and legitimacy resources, whereby material transfer, supply chain, and coalition building relationships form the valuation subsystem (Binz and Truffer 2020).

Together, the innovation mode and product valuation dimensions of the GIS create a two-by-two typology (Figure 2.1). This typology proposes four types of innovation systems based on their relationship to space and scale across their resource-based innovation subsystems. Innovation systems in which the innovation is more ST-based and product valuation is standardized are "spatially footloose," in that they are likely to have knowledge-related and valuation-related subsystems that have strong spatial spillovers and therefore link at higher spatial scales (i.e. "global") (Figure 2.1. Quadrant I). At the opposite end, "spatially sticky" systems represent a combination of DUI innovations and customized product valuation, where the knowledge-related and valuation-related subsystems are strong at the regional level (Figure 2.1. Quadrant III). The other two types mix these dimensions, where "market-anchored" systems have spatially footloose knowledge-related subsystems but sticky valuation-related subsystems, while "production-anchored" spatial scales are reversed across subsystems. Of course, these are stylized types that omit other complex dimensions. For instance, different parts of an innovation's value chain may exist in different quadrants of the typology (Rohe 2020), knowledge creation approaches may try to balance both ST and DUI modes (Jensen et al. 2007; Tsouri, Hanson, and Normann 2021), and placement on the typology may change over time (Binz

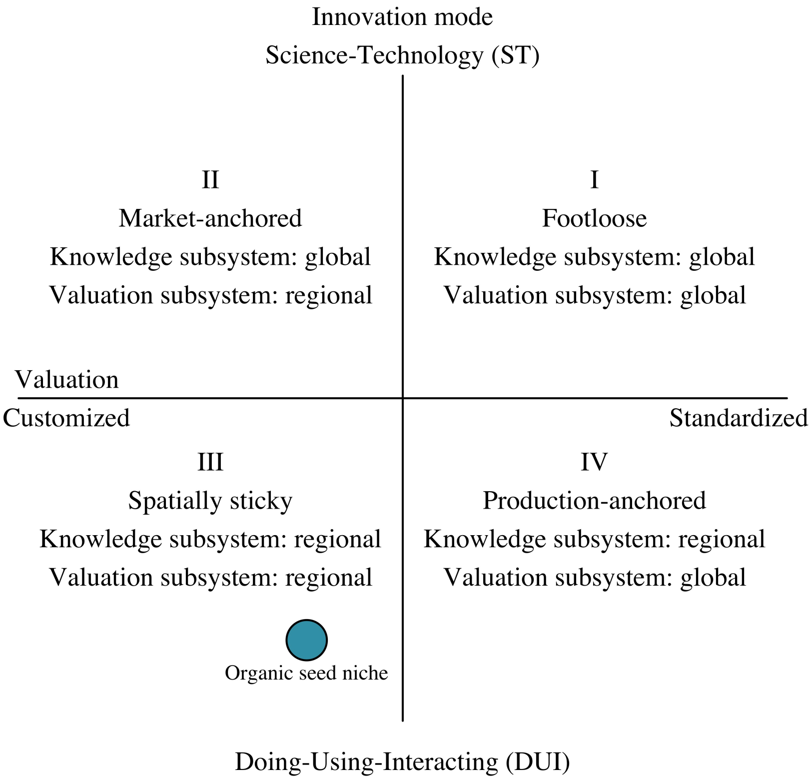

Figure 2.1: Global Innovation System typology, modified from Binz and Truffer (2017)

and Truffer 2017). However, this framework sets out a baseline for theory building across several complex dimensions, which helps develop a more generalizable understanding of how and why innovation systems evolve.

2.4 Organic seed innovation system

To test the GIS theory's propositions about IS spatial boundaries, we use the case of the organic seed system. Seed systems represent technological (and in some cases social) innovations for researching, producing, processing and selling seeds suitable for agricultural production (Almekinders and Louwaars 2002; Lammerts van Bueren et al. 2018). Seed researchers develop and test new plant varieties through breeding techniques, seed producers grow crops to harvest and sell their seed, and seed processors and companies are the industries that process the seed and sell it to consumers, from hobby gardeners to large scale crop producers. Additionally, there are organizations and government agencies that support several of these roles, including research, education, seed saving, and certification.

The *organic* seed system represents a niche that, at minimum, follows certified organic standards throughout the innovation's life cycle, and at most, represents an alternative social-ecological approach to genetic stewardship, land use, and community-building (Lammerts van Bueren et al. 2018). We base our study in the United States (US) organic seed system, but collect data so as to open the boundaries of our system beyond national borders, described in Section 3.1. In the US, certified organic crop production is a niche system supporting less than 1% of farmland (Bialik and Walker 2019), nested within the broader conventional agricultural innovation system. Historically in the US, the organic movement was borne out of a grassroots effort where the values of soil health and localized food systems are generally shared amongst the participants (Youngberg and DeMuth 2013). This ethic has extended to seed, where values of biodiversity stewardship, decentralized ownership, and producer sovereignty are prominent among organic seed stakeholders (Sievers-Glotzbach et al. 2020).

The organic seed niche theoretically aligns with the dimensions of a spatially sticky innovation system. While the knowledge to breed and produce seed certainly requires technical skills, agricultural production is a practice that is rooted to place. Furthermore, organic seed breeding permits only the use of traditional breeding methods (e.g. hybridization but not genetic modification) (Hubbard, Zystro, and Wood 2022), which places tacit knowledge, or doing-using-interacting innovation, at the center of organic plant breeding and production rather than science and technology.

Regarding valuation, the grassroots history of the organic movement has generated a market environment where products are valued for their regional adaptedness (Lammerts van Bueren et al. 2018; Rohe et al. 2022). Seeds that are adapted to the climates, soil types, pest pressures, and cultural histories of a given region are particularly important for organic production, both for optimal productivity as well as regional biodiversity maintenance (Hubbard, Zystro, and Wood 2022). This customized approach contrasts from conventional seed and crop valuation, which aims to create more spatially footloose products that can compete in a standardized commodity market (Rohe et al. 2022).[1]

2.5 Hypotheses

In this section we put forth hypotheses to test the Global Innovation Systems framework using the case of the organic seed system. We propose that the organic seed niche is po-

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[1] We do note, however, that as the organic niche stabilizes there is movement towards more standardized valuation to reflect the conventional market. For example, large conventional seed producers such as Bayer have recently begun to offer organic seed lines (Bayer 2021), showing some evidence of the niche approach being absorbed into the dominant model.

sitioned in the spatially sticky quadrant of Figure 2.1, dominantly in the DUI innovation mode and towards the center of the gradient in terms of product valuation. Based on these dimensions, we expect that the organic seed innovation subsystems' structures will generally align with the expectations of a regional, spatially sticky GIS type proposed by Binz and Tuffer (2017). Specifically, we hypothesize:

> H1a: The knowledge-related resource subsystem will be strongly coupled within regions, operationalized by regionally homogenous clans and within-region homophily
>
> H1b: The valuation-related resource subsystem will be strongly coupled within regions, operationalized by regionally homogenous clans and within-region homophily

Beyond coupling within-regions, we also evaluate vertical and horizontal structural coupling. While the GIS framework suggests that spatially sticky systems structurally couple within and between regions (Binz and Truffer 2020), there is less clarity on how national actors connect across scales, identified as the vertical coupling process. Thus we further the theory by proposing that within a regionally sticky system, higher-scale actors will provide both knowledge and market-based resources by acting as coordinators (Bergek et al. 2015; Vantaggiato et al. 2023). Specifically, we hypothesize:

> H2: National and international-scale actors will be serve as bridges between regional-scale actors, operationalized by national-scale actor heterophily and the prevalence of national-actor network connections

Further, we contribute to the developing examples of resource subsystem spillovers via horizontal coupling (Musiolik and Markard 2011; Rohe 2020; Tsouri, Hanson, and Normann 2021) by hypothesizing:

> H3: Actors' participation in one innovation subsystem will positively influence participation in the other, operationalized by positive correlation between the two subsystem networks

3. Methods

To test whether the organic seed network matches the expectations outlined by the GIS spatial framework we rely on social network methods. We operationalize the two innovation subsystems, knowledge and valuation subsystems, based on network questions posed in surveys distributed to organic seed innovation system stakeholders. We then summarize and analyze the two subsystems using two network approaches, structurally descriptive summaries based on clan composition and structurally explicit tests using Exponential Random Graph Models.

3.1 Organic seed system surveys

3.1.1 Innovation system stakeholder identification

We identified organic seed system stakeholder populations through two processes: An initial compilation of several stakeholder databases and a secondary snowball sampling process based on responses from the first round of data collection. For the initial process, we generated three databases with a total of 529 contacts. First, the USDA National Organic Program INTEGRITY database was manually reviewed, with the support of automated text methods, to identify 911 seed producers in the United States, 390 (43%) of which had valid email addresses and spatially identifiable operations. Second, 87 organic seed companies, based primarily but not entirely in the US, were identified by the national non-profit Organic Seed Alliance, who keep a database for their communication and research initiatives. Third, 52 organic seed researchers based in the US were identified by reviewing seed-related projects granted by major public and private organic grant funders (USDA -SARE, -OREI, -NIFA, OFRF, and Ceres Trust) and Web of Science publications over the last five years. This group included university, governmental, and non-profit researchers. Note that our initial population databases did not explicitly include governmental or non-governmental organizations, apart from those that were related to research.

For the second snowball process of identifying stakeholders, each survey included network questions about respondents' connections in the seed system (elaborated in Section 3.1.2). We used these responses to identify a snowball sample, from which there were an additional 227 seed system stakeholders identified, including 26 producers, 43 companies, 81 organizations, and 77 researchers (academic and governmental). While our initial database creation focused on US actors, the snowball process widened the scope of our respondents to include actors from other geographies. In total, we identified 756 actors in the organic seed innovation system, summarized by their geographic and scale categorizations in Table 2.1. While setting boundaries around innovation systems is a core challenge to the field (Bergek et al. 2008), we believe this identification approach captures a wide range of both formal and informal actors across multiple innovation system functions. And while our population started with a national focus, the snowball sampling approach accounted for the innovation system relationships that span territorial boundaries.

3.1.2 Survey development, distribution and sample

We conducted a series of online surveys with the four groups of organic seed stakeholders – seed producers, companies, researchers (including academics and government agencies), and organizations – between 2020-2022. The surveys asked respondents about their roles in the seed system and their networks: the people or organizations that they seek and exchange information with, who they collaborate with on research, who they work with along the supply chain, including seed contracts, equipment rental, and sales, and who they source germplasm from for breeding and exchanging seed.

Surveys were hosted on the Qualtrics survey platform and distributed over email. Each potential respondent was sent an initial email invitation with three reminders, spaced out every two to three weeks (Dillman, Smyth, and Christian 2014). Seed producers, researchers, and all snowball-sampled respondents were eligible for survey completion incentives. In the case of seed producers, respondents who completed the survey were put into a lottery system, in which 10 respondents were awarded $100 Visa gift cards. For seed researchers, each respondent earned a $40 award in the form of cash, gift card, or donation to an organization of their choosing. For the snowball sample, each respondent earned a $25 award in the form of cash, gift card, or donation to an organization of their choosing.

Out of those we surveyed, we have responses from 247 actors with a combined response rate of 33%. Based on data from the survey and supplementary seed stakeholder databases, we are able to add geographic and scale attributes to each actor that we surveyed. Geographically, we group our US regional respondents according to the US Department of Agriculture's Sustainable Agriculture Research and Education (USDA SARE) regions: West, North Central, South, and Northeast. We explore the implications of this regional boundary choice in Appendix B. Actors from these regions are represented as follows: 89 actors operating at the Western regional scale, 48 at the North Central regional scale, 41 at the Southern regional scale, and 27 at the Northeastern regional scale. There are also 11 respondents that operate at regional levels across Canada (CA), which we group into four governmentally designated regions: Pacific, Prairie, Central, and Atlantic (the fifth region, Yukon, was not represented). We also have two respondents from the regional scale in Mexico, listed under "Other country".

For actors that span regional administrative or operational scales, these were included in the analyses as national or international actors. We assign these scales based on government agencies' administrative role (e.g. federal agency), self-described national or international organizations, and size of company sales. Details on these scale designations are available in Appendix B. There were 23 survey respondents who operate at the national scale in the United States, four that operate at the Canadian national scale, and two that operate at the international scale.

3.2 Network construction

We constructed the innovation system network using survey questions related to actors' connections. These connections were elicited using the hybrid network question approach (Henry, Lubell, and McCoy 2012). Using this approach, respondents were asked to list up to five or ten people or organizations (number varied with question) that they look to, work with, or source from across several seed-related contexts. For each name they wrote, respondents had the option to select the modes of each connection. We match the types of connections to the functions described in the innovation system functional framework (Bergek et al. 2008): knowledge creation, resource mobilization, and market formation (Table 2.2). We then use these connections to create our key units of analysis: the two

Table 2.1: Organic seed innovation system sample population, survey response rate, and network composition by operational scale and geography

Scale	Geography	Population (N)	Sample (n)	Response (%)	Network actors (n)
Regional	West	334	89	27	194
	North Central	143	48	34	120
	South	94	41	44	87
	Northeast	75	27	36	59
	Pacific	17	6	35	13
	Central	8	3	38	8
	Prairie	2	1	50	3
	Atlantic	1	1	100	7
	Other country	2	2	100	14
National	USA	64	23	36	88
	Canada	7	4	57	14
	Other country	0	0	NaN	11
International	International	9	2	22	27
	Total	756	247	33	645

resource-based innovation subsystems as defined in the GIS framework (Binz and Truffer 2017). The knowledge subsystem includes connections related to information acquisition and exchange, research partnerships, stakeholder involvement in projects, and academic collaborations. The valuation subsystem combines the resource mobilization and market formation functions, which includes seed acquisition, seed exchange, research funding, licensing agreements, contracts, renting, buying, and/or selling to/from. These survey data do not include connection types that allow us to operationalize the legitimation function. Of the 247 survey respondents, 188 answered the network questions, and these respondents identified 497 other entities through 2395 connections. Because 20% (n=487) of the connections were to generic or non-identifiable stakeholders (e.g. respondents wrote in “other farmers” rather than “Starlight Farm”), they were excluded from the network structure (though the count of generic connections was included as a control variable). As a result, the final innovation system network includes a total of 1908 ties between 645

Table 2.2: Operationalization of resource-based innovation subsystems based on relationship types

Resource subsystems	Functions	Types of relationships
Knowledge	Knowledge creation	Information acquisition and exchange, Research partnerships, stakeholder project involvement, and academic collaborations
Valuation	Resource mobilization	Seed acquisition, seed exchange, research funding
	Market formation	Licensing agreements, contracts, rent, buy, and/or sell to/from

uniquely identifiable actors – referred to as nodes in social network analysis – across the different spatial scales (Table 2.1, Network actors column). For the sake of our analysis, we consider a network tie to be non-directed, meaning we assume the relationships go both ways, and we analyze each network without any weighting of the connections, reducing our number of ties from 1908 to 1206. For example, if actor A indicated multiple forms of knowledge development with actor B (academic collaboration and research project development), this counts as only one tie.

3.3 Social network analyses

We run two analyses to explain how the two resource-based subsystems in the organic seed network are coupled: structurally descriptive n-clan approach and a structurally explicit Exponential Random Graph Modeling (ERGM) approach. In both approaches we aim to analyze coupling within the regional scale (i.e. “regional”), within the higher scales (i.e. “global”), and between regional and higher scales.

3.3.1 Geographic and scale composition across n-clans

We first describe our innovation network by summarizing the spatial representation of actors across the two innovation subsystems by scale and geography. We further this description by evaluating the composition of spatial representation across clans in the subsystems. Clans are cohesive subgroups within a network where the greatest distance between any two nodes in the subgroup is no larger than the assigned path length value (n) (Binz, Truffer, and Coenen 2014; Wasserman and Faust 1994). We identify clans with a maximum path length value of 2 for each innovation subsystem to detect small, cohesive units.

Once we identify the clans, we then categorize each of them based on their spatial composition, which we determine based on actors' geographic and scalar positions, guided by methods in Binz et al. (2014). If the composition of a clan is dominated by a majority (>50%) of a particular geographic region or scale, that clan is assigned to have either a "within-region," "within-nation," or "within-international" composition. These are subgroups where the majority of actors are within one specific geographic region or scale, for example, Western regional or US national actors. If the composition of the clan has no majority representation from a region but consists of actors all of the same scale (e.g. all regional actors split between the West, North Central, and South regions or all national actors split between US and Canada), the clan is assigned to a "between-region" or "between-nation" composition. There is no option for a "between-international" composition as international actors are not assigned a geographic location and so international is a singular category. Last, if a clan has no dominant region or dominant scale represented and mixes regional, national, and/or international scales, it is assigned to a "mixed-scale" composition.

In short, the n-clan approach provides a cursory look at what geographic and/or scale attributes dominate within small communities of the subsystem. This analytical approach is considered structurally descriptive, in that we utilize our network data to summarize spatial information about our innovation subsystems (Scott and Ulibarri 2019). These n-clan categorizations can suggest a trend in spatial structure, but this method is unable to statistically test within or between scale preference and prevalence.

3.3.2 ERGMs

To expand on the n-clan descriptive approach, we propose Exponential Random Graph Models (ERGMs) (Lusher, Koskinen, and Robins 2012), a structurally explicit way to statistically infer meaning from network structures (Scott and Ulibarri 2019). ERGMs are a well-developed network method (Lubell et al. 2012) that estimate the likelihood that a network tie will form based on endogenous and exogenous predictors (Robins, Lewis, and Wang 2012). Endogenous predictors are the features of the network itself, such as the number of connections and nodes, open and closed triangle formations, among many others. Exogenous predictors are features of the nodes in the network, which in the case of this study include an actors' spatial attributes. An ERGM estimates the likelihood that these endogenous and exogenous features influence tie formation in the observed network by simulating thousands of random graphs that have the same structural parameters as those specified in the model (Robins, Lewis, and Wang 2012).

To test our hypotheses regarding the spatial structure of the organic seed innovation system, our results focus on two exogenous actor attributes and one endogenous parameter. The focal exogenous attributes are the geography and scale of actors in the network. To test whether there is within region or within nation affinity in each subsystem (H1), we use a homophily parameter for the combined geographic and scale attributes. The homophily parameters in our model represent the probability of an actor to preferentially connect to actors within their own geography or scale. Second, to test the activity of actors operating at certain scales (H2), we include a node covariate for the scale attribute (regional, national, or international). These parameters indicate the probability of forming a tie for an actor that operates at the national or international scales compared to an actor that operates at the baseline regional scale. The focal endogenous parameter in our model is a matrix representing the structure of the subsystem not being tested (e.g. when evaluating the knowledge subsystem, the matrix represents the structure of the valuation subsystem). This matrix, included in the model as an edge covariate, allows us to test the strength of horizontal coupling between resource subsystems (H3).

We also include seven control variables. The first three, edges, degree, and triadic closure, are common structural parameters to account for social processes that take place in the network (Lusher, Koskinen, and Robins 2012). Edges represent a baseline probability a forming a tie, degree (specified with geometrically weighting, “gwdegree”) represents the network’s tendency towards centralization, and triadic closure (specified as geometrically weighted edgewise shared partners, “gwesp”), represents the likelihood of a connection to close a triangle (Levy and Lubell 2018).

The last four parameters are controls to account for the effect of the data collection process on network sampling. These include a count of the number of individuals that answered on behalf of one organization, as these multi-respondent nodes had more chances to identify connections compared to nodes with only one respondent. Second, we have a variable representing the number of generic and/or non-identifiable ties an actor had to account for actors’ connectedness that we could not make explicit in the network. Third, we include a binary variable representing whether or not a stakeholder responded to the survey, as non-respondents are likely to have fewer ties given that they could not identify their relationships. Relatedly, our last control parameter is a matrix of structural zeroes to specify that it was impossible for two actors, neither of which responded to the survey, to have a connection (Scott and Thomas 2015).

We estimate two ERGMs, one for each innovation subsystem, in order to identify the variables that most influence network formation. All analyses were conducted using R statistical software (Team 2023), relying primarily on the statnet package (Krivitsky et al. 2022) for analysis. Code for analysis is available at github.com/liza-wood/osisn_spatial.

4. Results

4.1 Innovation subsystem and n-clan spatial composition

The organic seed innovation system identified through our survey methods includes 645 stakeholders forming 1908 connections (1206 when unweighted). Between the two innovation subsystems, the knowledge subsystem is slightly larger, where 522 actors account for 1106 connections (815 when unweighted), while in the valuation subsystem includes 418 actors accounting for 802 connections (643 when unweighted) (Table 2.3). Across the different geographies, actors operating in different regions in the US account for about 76% and 69% of the knowledge and valuation subsystems, respectively. Actors operating at the US-national scale represent 12% and 16% of the networks, international-scale actors account for 4% and 3% of the networks, and the remaining 8-12% of actors are from various regional and national scales. The majority of these remaining actors are from Canada, though there are also 20 actors from both scales represented as “Other country” from various global contexts. Across both subsystems, the majority of actors are connected as one component (95% in the knowledge subsystem and 90% in the valua-

Table 2.3: Actors' geographic and scale representation in resource-based innovation subsystems by count and percent

Scale	Geography	Knowledge subsystem	Valuation subsystem
Regional	West	160 (31%)	142 (34%)
	North Central	107 (20%)	75 (18%)
	South	76 (15%)	42 (10%)
	Northeast	51 (10%)	28 (7%)
	Pacific	6 (1%)	12 (3%)
	Central	6 (1%)	5 (1%)
	Prairie	3 (1%)	1 (0%)
	Atlantic	3 (1%)	5 (1%)
	Other country	9 (2%)	10 (2%)
National	USA	64 (12%)	66 (16%)
	Canada	11 (2%)	8 (2%)
	Other country	3 (1%)	10 (2%)
International	International	23 (4%)	14 (3%)
	Total	522	418

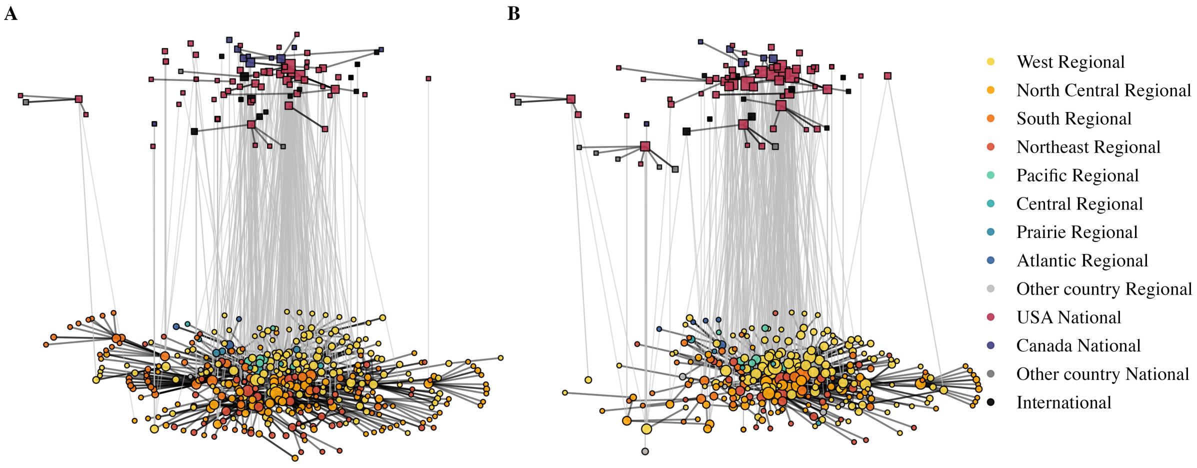

Figure 2.2: Network graphs of the organic seed resource-based subsystems: A) knowledge subsystem and B) valuation subsystem. Circles represent actors/organizations and lines represent connections based on the different relationships within each subsystem. Nodes are sized by their relative popularity (the larger, the greater number of ties they have) and colored based on their combined geographic and scale attributes, identified in the legend. Each network is separated into levels based on scale, where regional actors are located on the lower level, circle shapes, and national and international actors are located on the higher level, represented by square shapes.

tion subsystem), meaning nearly every actor can connect to another by different "paths." The main component of each of the two innovation subsystems are visualized in Figure 2.2. The n-clan detection identified 166 clans in the knowledge subsystem and 150 in the valuation subsystem, with average sizes of 9 and 8 actors per clan, respectively. On average, actors in both subsystems belong to 3 clans, suggesting that there are several overlapping subgroups within each subsystem.

A summary of the clan composition (Table 2.4) describes how the geographic and scalar attributes of actors influence their connections. First, around half of the clans are classified as having within-region composition for both the knowledge and valuation innovation subsystems (60% and 48%, respectively). This means that these closely knit subgroups are defined by actors within the same region, such as US Western-region actors connecting to one another or Canada's Atlantic-region actors connecting to one another. On the other hand, between-region clans where all actors operate at the regional scale but no single region is in the majority, account for only 1% of the clans in each subsystem.

Second, we see 33% (knowledge) and 43% (valuation) of the clans being defined as mixed-scale composition. This means that no particular geography or scale represents the majority of actors in the clan. Instead, actors from different regions and scales are all connected. On average in these mixed-scale clans, national-scale actors represent 29% (knowledge) and 35% (valuation) of the actors, and the remaining actors are from different geographies at regional or international scales. At the national scale, we see only 5% and 8% of clans representing within-nation composition, such as national US actors interacting mainly with other national US actors, and no between-nation clans.

Table 2.4: Composition of innovation subsystems by clan count and percent

Composition	Knowledge subsystem	Valuation subsystem
Within-region clans	100 (60%)	72 (48%)
Within-nation clans	9 (5%)	12 (8%)
Within-international clans	0 (0%)	0 (0%)
Between-region clans	2 (1%)	1 (1%)
Between-nation clans	0 (0%)	0 (0%)
Mixed-scale clans	55 (33%)	65 (43%)

Together, these n-clan compositions suggest that both the knowledge and valuation subsystems are composed largely of regionally close-knit clans, which shows support for H1. And when national-scale actors are involved, they are most active in subgroups with actors at other scales (typically regional) rather than with one-another, lending support for H2. Furthermore, we look at the correlation between the two subsystem matrices and find a positive correlation coefficient of 0.41, suggesting similarity but not full overlap in the networks, lending support for H3.

4.2 Network inferences on structural coupling

Next we present results from our two Exponential Random Graph Models, which estimate the likelihood of forming a tie in the innovation subsystem based on actors' spatial attributes and activity across subsystems. Figure 2.3 displays the coefficient estimates and confidence intervals for the variables of interest in our two ERGMs, reported as log-odds. Full model results are available in Appendix B. When interpreting log-odds, a basic intuition is that values less than zero represent lower probabilities of forming a tie and values greater than zero represent higher probabilities of forming a tie. Estimates are considered statistically significant if they do not cross over zero. To discuss specific statistics throughout the text, we transform the log-odds coefficients into odds.

4.2.1 Organic seed as a spatially sticky innovation system

Network homophily, the tendency for actors with shared attributes to form connections, can provide insight into our first hypothesis regarding the spatial stickiness of the organic seed innovation subsystems. The homophily terms in the models represent the likelihood of an actor from a certain region or scale (i.e. four regions in the US or the US national scale) forming a tie with an actor from that same region or scale. We report homophily only for actors from the US regions and national scale because the number of actors from other scales were too small to be estimated.

Across both innovation subsystems, actors from each region – Northeast, North Central, South, and West – are all significantly more likely to have connections to actors within their own region, rather than outside it. When transforming the log-odds estimates for the knowledge subsystem, actors from each respective region have odds of 19.1, 9.3, 8.5, and 3.6 to 1, all of which are quite large. When transforming the log-odds estimates for the valuation subsystem, actors from each respective region have odds of 12.5, 2.9, 3.8, and 4.2 to 1.

In short, actors that operate at a regional scale are highly likely to connect to actors within their region, creating robust regional networks. These results align with the n-clan descriptions to support H1a and H1b, as there is strong within-region affinity for both subsystems, representing regional stickiness of the organic seed innovation system. Furthermore, regional affinity is slightly higher, on average, in the knowledge subsystem compared to the valuation subsystem, supporting our placement of the organic seed system more towards the center of the valuation axis (Figure 2.1).

4.2.2 Vertical coupling via national-scale bridges

Network statistics about the homophily and activity of national and international scale actors are relevant to our second hypothesis, as they evaluate vertical coupling in the organic seed subsystems. The national homophily term in Figure 2.3 demonstrates that actors who operate at the US national scale are significantly less likely to connect to one another in both the knowledge and valuation subsystems. For both subsystems, the odds of a US national actor forming a tie with another US national actor are small: 0.4 to 1. Thus in the organic seed subsystems national actors are not interacting with other national actors, but instead may be serving as bridges between regional-scale actors.

The role of higher-scale actors as bridges is further supported by the positive and significant estimates for tie formation at the national and international scales. Where homophily represents the probability of a connection to those with a shared attribute,

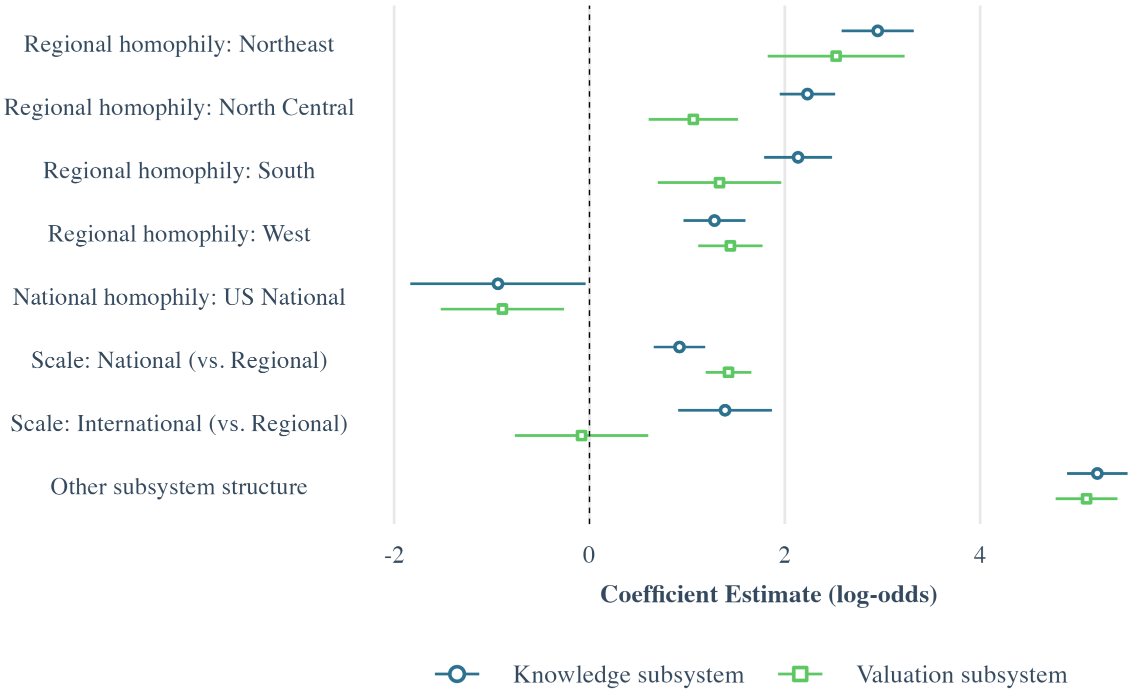

Figure 2.3: Coefficient plot for ERGMs of the knowledge and valuation subsystems. Shapes represent the coefficient estimate, reported as log-odds, and bars represent confidence intervals.

the scale term in the model represents the estimated likelihood of an actor to form a tie generally, compared to the baseline of regional-scale actors. Compared to this baseline, the odds for a national-scale actor to form a tie are 2.5 to 1 in the knowledge subsystem and 4.2 to 1 in the valuation subsystem. For international actors, these odds are 1 to 1 and 0.9 to 1, respectively, though the valuation subsystem estimate is not significant. In short, network connections to higher-scale national and international actors are more likely than connections to regional-scale actors, highlighting their popularity in the network.

The models' results support H2, suggesting vertical coupling via higher-scale actors who are strongly linked to regional actors but not to one another. These results align the descriptive n-clan analysis, which found very few within-nation clans, but instead, identified national-scale actors most prominently in mixed-scale clans.

4.2.3 Horizontal coupling via subsystem spillover

Last, the activity of actors across both subsystems can provide insight into our third hypothesis regarding horizontal coupling between the knowledge and valuation innovation subsystems. In other words, how network formation in one resource subsystem affects the other. The "other subsystem structure" term in the model represents how the presence of a connection in one subsystem affects the likelihood of forming a connection in the other. Consistent with H3, we find a large and significant effect of the other subsystems' structure on the evaluated subsystem. Actors who have connections in one subsystem are highly likely to form connections in the other, with odds of 181 and 162 to 1 for the knowledge and valuation subsystems, respectively.

5. Discussion

5.1 Developing GIS theory

Results from our analysis of the organic seed system align with the expectations of the GIS framework. For the organic seed case, which has a strong DUI innovation mode and customized product valuation, both the knowledge and valuation resource-based subsystems have strong within-region affinity (i.e. they are spatially sticky). By finding support for the GIS typology, this paper contributes to the theory-building effort of the framework: to identify the conditions under which innovation systems form and build resources (Binz and Truffer 2017). This contribution is part of a broader effort to add theoretical depth to innovation systems scholarship and advance a generalizable understanding of system formation and boundaries (Markard, Hekkert, and Jacobsson 2015).

This paper is among the handful of studies that have begun to test the GIS framework across different empirical cases (MacKinnon, Afewerki, and Karlsen 2022; Rohe 2020; Tsouri, Hanson, and Normann 2021). The majority of these studies relate to alternative energy technologies (e.g. wind power), which represent a mix of sticky and footloose spatial structures that rely, to some extent, on strong global networks. These cases reflect a trend in sustainability transition cases more generally, which tend to focus on innovations that rely more on codified ST-based knowledge and products with more standardized valuation (Köhler et al. 2019). Under the conditions of a DUI innovation mode and customized product valuation, as in the organic seed case, we provide an important complement to existing studies and highlight the importance of regionally-based networks (Rohe and Mattes 2022).

The recognition that IS boundary-setting varies based on certain conditions has important implications for the field. For innovation studies researchers and policy makers alike, these conditions serve as a guide on how to best select boundaries, which has important consequences for measuring the development and success of an innovation system (Binz, Truffer, and Coenen 2014; Wieczorek et al. 2015), as well as developing effective policies.

Beyond validating the theory outlined by the GIS framework, we also add nuance to the understanding of how subsystems link to one another within and across space by testing the prevalence of both vertical and horizontal coupling within the organic seed system (Rohe 2020; Tsouri, Hanson, and Normann 2021). We find that even in an IS rooted in strong regional networks, higher-scale actors at the national and international scales have important roles to play as bridges between regional networks. This result aligns generally with expectations highlighted in the geography and innovation systems literature (Binz, Truffer, and Coenen 2014; Wieczorek et al. 2015) and more broadly in governance network studies (Vantaggiato et al. 2023).

Relevant to the vertical coupling results, we want to emphasize a distinction between two types of vertical coupling that we don't think have been delineated clearly enough in the developing theory. First, there is coupling between geographies of the same scale, what MacKinnon et al. (2022) refer to as trans-regional coupling, which we operationalize as between-region clans and within-region heterophily. Second is coupling between lower and higher scales, which we operationalize as mixed-scale clans and infer from the national scale actors' heterophilic tendency (i.e. preference to create ties with non-national actors) and strong probability of tie formation compared to regional actors. We believe that researchers should continue to identify the different ways in which actors' scales and roles affect the types of coupling they engage in, and the different structural forms that coupling can take (e.g. "partner" or "intermediary" modes (Musiolik et al. 2020)).

Regarding horizontal coupling, the effect of one resource-based subsystem on another, we find evidence for strong spillover effects between subsystems. In the organic seed system, actors' participation in one innovation subsystem positively influenced participation in the other, pointing to the multi-functionality of network relationships (Vantaggiato and Lubell 2022). While our analysis is not able to distinguish the effect of scale on spillover, which has been relevant in other cases (Tsouri, Hanson, and Normann 2021), it is a first step to quantify horizontal coupling using network methods.

5.2 Contributions to innovation system network methods

The analytical approaches used in this paper add to the methodological toolkit of innovation research. While network analysis is certainly not new to innovation studies (Alphen et al. 2010; Hermans, Stuiver, et al. 2013; Musiolik, Markard, and Hekkert 2012), we employ an Exponential Random Graph Modeling approach which is seldom applied in this field (Hermans et al. 2017). We link the results from the ERGM to a network approach previously applied to innovation systems, n-clan composition (Binz, Truffer, and Coenen 2014), to provide a bridge between descriptive methods (Giurca and Metz 2018; Rohe and Chlebna 2022) and structurally explicit methods (Scott and Ulibarri 2019).

The application of ERGMs in this paper heeds the call for new, rigorous methods for analyzing innovation systems (Binz and Truffer 2017; Binz, Truffer, and Coenen 2014) and sustainability transitions more generally (Köhler et al. 2019). And indeed, it is among other quantitative contributions for enriching the way we understand relational data (Heiberg, Truffer, and Binz 2022), and it is a complement to the studies that have analyzed GIS using qualitative methods (MacKinnon, Afewerki, and Karlsen 2022; Rohe 2020).

5.3 Limitations

While the data collection approach used in this research aimed to include all relevant geographies and scales, our methods have their shortcomings. First, our sampling approach allows us only to discuss the spatial reach of the organic seed system *with a starting point in the US*. We used the US organic seed system population as a starting point, then sampled to be inclusive of all geographies and scales reported by the system's actors. Recognizing the starting point of our sample, we do not propose this to be a global representation of the organic seed system. Rather, we have focused on the US organic seed system and allowed snowball sampling to define the boundaries according to the responses, which permits us to evaluate the system without pre-specifying its limits. Second, survey methods can be limiting. Surveys have the benefit of actors self-identifying their connections, which may represent a more genuine connection than codified relationships such as co-authorship or joint project participation. The drawback, however, is that surveys are challenging to collect, limited to the time of data collection, and suffer from low response rates. As such we are capturing only a sample of the innovation system population, and generalize our findings based on their representativeness. Future work should remain cautious about how data collection processes affect conclusions about system boundaries.

6. Conclusion

In this paper, we address a question of both academic and policy relevance in innovation studies: *What determines the spatial boundaries of an innovation system?* We develop three hypotheses to test the theory put forth by the Global Innovation Systems framework (Binz and Truffer 2017; Rohe 2020; Tsouri, Hanson, and Normann 2021). We use the case of the organic seed system, a niche with a DUI innovation mode and relatively customized type of product valuation, to validate the GIS typology and extend our understanding of structural coupling within and between innovation subsystems. By applying structurally explicitly network analysis, Exponential Random Graph Models, we confirm the expectations outlined by the GIS and add nuance to the understanding of how actors link to one another within and across spatial scales. These results contribute to the theoretical underpinnings of the GIS framework, as well as add to the methodological toolkit for analyzing innovation systems using inferential network analysis.

In practical terms, understanding the spatial boundaries most relevant to an innovation system can help policymakers identify the scope of relevant policy. In organic seed, for example, recognizing its spatial stickiness highlights the importance of supporting regional seed policies, such as state-specific protections for genetic contamination, to help meet the customized needs of an area (Alliance 2022). Though at the same time, policy should leverage the bridging role of higher-level national actors as connectors of limiting resources like funding and providing pre-competitive resources like genetic material.

Chapter 3

Resource constellations and institutional logics shape network-building processes in the organic seed niche

1. Introduction

How to build a successful innovation system has long been a topic in the sustainability transitions literature (Hermans, Klerkx, and Roep 2015; Klein Woolthuis, Lankhuizen, and Gilsing 2005). Much attention has been paid to the functions that support innovation systems, such as knowledge creation, legitimacy building, resource mobilization, and market formation, which are the processes fueling the development and diffusion of an innovation (Bergek et al. 2008). Complementary to these functions are structural features, which define the architecture that helps these functions develop, accrue, and/or dissolve (Wieczorek and Hekkert 2012).

While it is broadly agreed that there is no single recipe for how innovation systems are built (Bergek et al. 2008), recent work proposes conditions that predict stylized types of structures (Binz and Truffer 2017; Binz, Truffer, and Coenen 2014; Hermans, Van Apeldoorn, et al. 2013). Of particular interest in this paper is the resource-based theory for system building (Musiolik et al. 2020; Musiolik, Markard, and Hekkert 2012), where the availability and distribution of resources (i.e. resource constellations) predict the types of structures that network actors form. Yet, empirically testing this theory is still in early phases (Célia Cholez and Marie-Benoît 2023), and so this paper takes the opportunity to examine and extend the theoretical underpinnings of network formation and actors' roles in building innovation systems.

In this paper we ask: *What are the conditions driving innovation system formation? And what types of actors are most involved in the formation of innovation networks?* We connect the resource-based theory for network building (Musiolik et al. 2020) to governance and social network literature (Prell and Skvoretz 2008; Provan and Kenis 2008) to develop a testable hypothesis about the relationship between system resources and network structure. Specifically, we test whether "partner modes" of system building, represented by closed triangle structures in a network, will be more prevalent than "intermediary modes," represented by open triangles, in innovation system networks that have existing, decentralized resources. We then draw on the multi-actor perspective (Avelino and Wittmayer 2016) to extend this theory and hypothesize how actors' institutional logics influence their activity across different subsystems in the network. We propose that non-profit stakeholders will be more active in the subsystems formed to generate knowledge resources, and for-profit stakeholders will be more active in subsystems formed around valuation resources like mobilizing funding, value chain creation, and market formation.

We test these hypotheses using the empirical case of the United States organic seed niche innovation system. We construct an innovation system network of over 600 actors using survey data collected between 2020-2022, and operationalize two resource subsystems – knowledge and valuation subsystems. Based on these data, we use a structurally explicit network analytical approach, Exponential Random Graph Modeling, to statistically determine whether certain network-building processes and actor compositions are more or less prevalent in the organic seed niche's resource subsystems.

Our results point to two main findings. First, we provide empirical support for the resource-based theory, which predicts innovation system structure based on resource constellations. Both the knowledge and valuation resource subsystems in the organic seed system have existing but decentralized resources, and these networks rely significantly more on partner modes of system building (closed triangle structures) than intermediary modes (open triangles). Second, we find support for our hypotheses about actor composition, where actors' institutional logics align with their relative activity in the different resource subsystems. Apart from government, non-profit actors are more active in the knowledge subsystem, aligning with pre-competitive logics, while for-profit actors are more active in valuation subsystems, aligning with more competitive logics.

Altogether, these results confirm the expectations outlined by the resource-based theory for system building and add nuance to the understanding of when certain actors are more or less likely to be involved. By furthering our understanding about the building blocks of innovation systems, these findings can help policymakers identify the circumstances under which certain system building strategies should be put into place. Furthermore, we agree with Musiolik et al., that "in order to better understand and improve system performance, we have to look into the processes through which technological innovation systems are intentionally created" (2012, 1034).

This paper will be structured as follows. In Section 2 we review existing literature on the structural building blocks of networks and the resource and actor-based attributes that theoretically shape innovation system structure. We then describe our case of the organic seed system and the kinds of networks it includes. In Section 3 we describe our research methods, including our data collection, network construction, and social network analysis methods. Next we describe our results in Section 4, which include descriptions of organic seed system resources and subsystems, and inferences about network structure and composition. Last, we discuss the results and their implications in Section 5 and conclude in Section 6.

2. Background

2.1 The structural building blocks of networks

2.1.1 Modes of innovation system building

How social and technological innovations develop and diffuse is of central interest to innovation system (IS) research. The functional and resource-based frameworks of innovation systems (Bergek et al. 2008; Musiolik, Markard, and Hekkert 2012) have been influential in delineating the processes that foster an innovation system's formation. For example, functions like knowledge development and diffusion, legitimation of the technology, resource mobilization, and market formation provide key resources necessary to support an innovation's success (Binz, Truffer, and Coenen 2016). The functional perspective initially argued that the structure of an innovation system – who is involved and how they are connected – is an emergent property for which there was no single recipe (Bergek et al. 2008). However, scholars argue that this approach removes agency from IS studies

(Farla et al. 2012; Musiolik, Markard, and Hekkert 2012), which has in turn minimized attention on the structural building blocks of innovation systems.

Yet, the structure of innovation systems has made a come-back in recent research (Binz and Truffer 2017). One key area of interest is how actors employ different modes of "strategic system building" to develop IS networks (Célia Cholez and Marie-Benoît 2023; Musiolik et al. 2020). System building is the creation and strengthening of innovation system-wide resources, including functions[1] like shared knowledge, legitimation, market formation, and value-chain creation (Hellsmark and Jacobsson 2009; Musiolik and Markard 2011; Musiolik, Markard, and Hekkert 2012). Recent research has focused on how these system resources are intentionally developed by building relationships, specifically within formal networks (Musiolik and Markard 2011).

Systems building theory lays out two types of multi-actor structures within IS networks that can support system resources (Musiolik et al. 2020). The first is "partner mode," where actors in the network share complementary skills and assets to co-create resources that support system-level functioning. The second is "intermediary mode," where actors work together via an intermediary actor that can generate resources to support both network-level functioning, such as trust and reputation, as well as systems-level functioning (Musiolik et al. 2020). The two structures are displayed in Figure 3.1A. The key structural difference is that the intermediary modes require the creation of network resources, and so "a system builder coordinates activities in a network of collaborators to develop new, intermediate organizational structures" (Musiolik et al. 2020) (10). We use

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[1] System resources (also called "elements") and IS functions generally map onto one another (Binz, Truffer, and Coenen 2016; Musiolik and Markard 2011). Musiolik et al. describe: "System elements provide positive externalities such as public financial support, the deliberate diffusion of knowledge or the creation of legitimacy. These contributions at the system level can be allocated to the system functions and indicate how important the identified system elements for TIS development are." (2011, 1919). While some elements such as value chain coordination are not in the traditional list of functions (Bergek et al. 2008), in this paper we generally think of "functions" and "system resources" as interchangeable, and try to primarily use the resources language over the functional language.

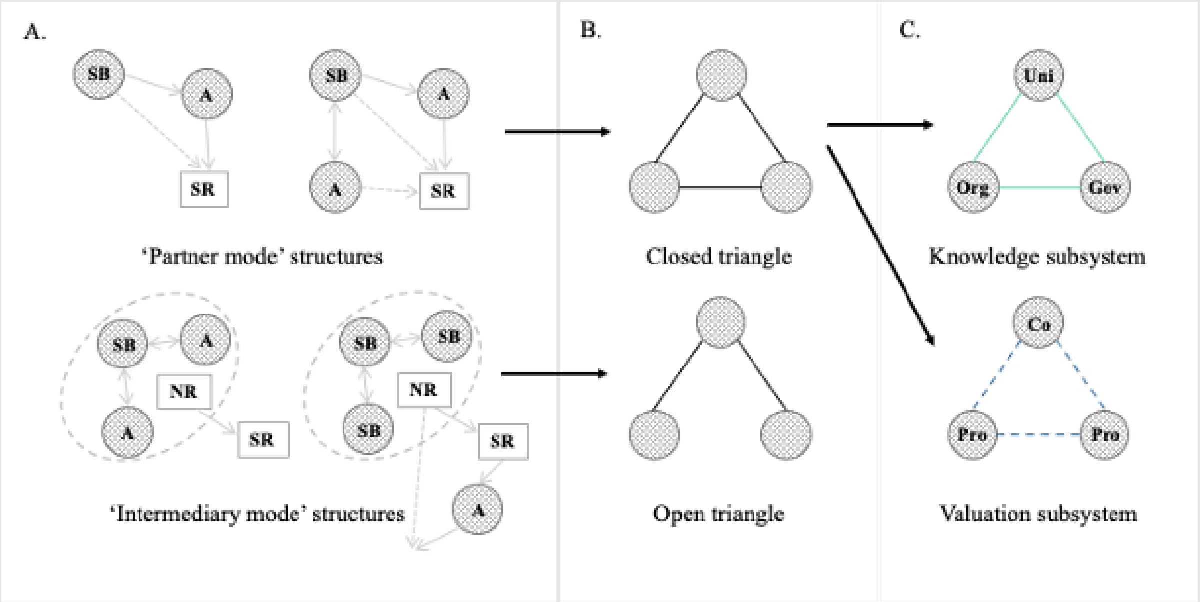

Figure 3.1: A) Multi-actor network structures, adapted from Musiolik et al. (2020). Partner mode structures (top) and intermediate mode structures (bottom) show how system builders (SB) connect to complementary actors (A) to build system resources (SR) and network resources (NR). B) Social network motifs, closed triangles (top) and open triangles (bottom), which align with the modes in panel A. C) Examples of two closed network structures, each representing relationships formed in different resource subsystems: the knowledge subsystem (top, blue solid connecting lines) and the valuation subsystem (bottom, green dashed connecting lines). Actor composition varies based on subsystem, with different combinations of universities (Uni), organizations (Org), government (Govt), companies (Co), and producers (Pro).

these structures as a starting point for linking the innovation systems and social networks literatures.

2.1.2 Social network motifs

Theoretical and methodological traditions in social network analysis can help further our understanding of network structuring modes studied in innovation systems. While a growing number of studies operationalize innovation systems as networks (Alphen et al. 2010; Binz, Truffer, and Coenen 2014; Fernandez de Arroyabe Fernandez et al. 2020;

Giurca and Metz 2018; Rohe and Chlebna 2022) few connect to the theory on network structure (Hermans, Van Apeldoorn, et al. 2013; Hermans et al. 2017).

Studies of social networks have long recognized that networks are made up of structural building blocks (Lusher, Koskinen, and Robins 2012). These structural building blocks, also called motifs, are the quantifiable foundations of a network that researchers use to develop and test social network theories (Bodin and Tengö 2012; Burt 2000; Granovetter 1973). For example, two motifs that have been central to network research are open and closed triangles (Berardo and Scholz 2010; Vantaggiato and Lubell 2022) (Figure 3.1B). These structural motifs are linked to different social processes of network building, and come by many names (Levy and Lubell 2018; Prell and Skvoretz 2008).

Open triangles depict one actor connecting two other actors who are otherwise not connected, also referred to as brokerage (Burt 2005). This open triangle motif, measured by a network's centralization, is associated with efficiency and reduced transaction costs, supporting social processes like coordination as a small handful of actors take on centralized leadership roles (Berardo and Scholz 2010; Burt 2000). On the other hand, a closed triangle depicts three actors who are all connected to one another, also referred to as closure (Burt 2005). This configuration, measured by a network's triadic closure, suggests cooperative social processes like co-development and exchange of ideas, trust-building, and cohesion (Berardo and Scholz 2010; Prell and Lo 2016). The exact social processes associated with these structures are contested (Prell and Skvoretz 2008) and they are not mutually exclusive (Levy and Lubell 2018; Vantaggiato and Lubell 2022), but still they serve as useful building blocks for developing and testing theory.

We propose that the partner and intermediary modes put forth by Musiolik et al. (2020) map onto the closed and open triangle motifs used in social network research. The partner mode of system building is akin to closed triangles, where partnerships are primarily about cooperating to share complementary resources (Musiolik et al. 2020). The intermediary mode of system building is akin to open triangles, where the systems-level deficits are more complex and network-level resources like coordination are required to support building up of system resources (Musiolik et al. 2020; Musiolik, Markard, and Hekkert 2012). A note is that though the partner mode configurations all structurally look like open triangles in their original conception (Figure 3.1A), we argue that the theoretical underpinnings of this structure align with those of closed triangles.[2]

By linking the resource-based IS theory to social network theory, we can use social network methods to test and extend our understanding of innovation system formation. While several studies have recently used networks to *describe* innovation systems (Alphen et al. 2010; Binz, Truffer, and Coenen 2014; Giurca and Metz 2018; Rohe and Chlebna 2022), only small handful of innovation systems papers have employed *inferential* network analysis, such as testing for network-level cooperation and identifying prominent types of actors (Hermans, Van Apeldoorn, et al. 2013; Hermans et al. 2017). We propose that inferential network analysis can help us test and advance existing IS network building theory (Scott and Ulibarri 2019), serving as a complement to existing qualitative and quantitatively descriptive studies.

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[2] We believe that the structures observed by Musiolik et al. (2020) are limited based on the authors' ego-centric interview methods (Chung, Hossain, and Davis 2005) which relied largely on the perspective of key actors to describe how networks are formed by system builders only. A comprehensive sampling method that gathers data on all actors' connections would be able to more fully represent the network structures and likely show closure of triangles in the cases of partner mode structures.

2.2 Attributes shaping innovation system network structure

2.2.1 Resource-based conditions across subsystems

In this paper we contribute to a central question in innovation system network research: What are the conditions driving innovation system formation? Recent theoretical developments identify several conditions predicting different structural configurations (Binz and Truffer 2017; Musiolik et al. 2020). To describe system building, Musiolik et al. (2020) put forth a resource-based approach to predict whether multi-actor network structures will pursue partner or intermediary modes. This approach proposes that actors pursue different structures based on resource availability and resource concentration within the system, also called resource constellations. If the resources (e.g. skills or assets) needed to support a systems-level resource (e.g. knowledge diffusion and market formation functions) already exist but are dispersed among different actors, a partnering structure is more likely. On the other hand, if the resources are non-existent in the innovation system, the intermediary mode of structuring is more likely to support the creation of new network and systems-level resources (Musiolik et al. 2020).

This resource-based reasoning of system building resembles the logic of other social network theories, particularly those from network governance. Network governance theory proposes that network structure is dependent on a handful of contingencies, one of which is the "need for network-level competencies" – a concept closely aligned to network resources like trust, legitimacy, and coordination to address complex problems (Provan and Kenis 2008). When the need for these network-level competencies is high, networks will be coordinated by a lead or external agency with high centralization (open triangles) rather than cooperation (closed triangles) (Lubell, Jasny, and Hastings 2017). On the other hand, when the need for network-level competencies is low, networks will take a participant-led approach where actors partner to co-create complementary alliances (Rudnick et al. 2019).[3] These network governance concepts map well onto intermediary and partner modes (Musiolik et al. 2020), and help align them with network motifs.

Identifying network building processes is challenging because networks are multi-functional (Vantaggiato and Lubell 2022). Actors often engage in several different kinds of relationships that address different resource needs. Networks can help actors create and exchange knowledge, develop contracts, mobilize resources, and/or connect along the value chain (Binz and Truffer 2017; Giurca and Metz 2018; Spielman et al. 2011). This is especially true as relationships build over time, blurring the exact functional purposes of a network connection (Oh, Chung, and Labianca 2004). For example, agricultural production contracts were designed to support market development and resource mobilization within the value chain, but as a byproduct they also support knowledge development and exchange (Celia Cholez, Magrini, and Galliano 2020).

To capture the multi-functional complexity of IS networks, we conceptualize innovation systems as a series of interdependent "resource subsystems." We follow the typology developed by Binz and Truffer (2017), recognizing a knowledge subsystem, composed of knowledge development and diffusion functions, and a valuation subsystem, composed of resource mobilization, market formation, and value chain coordination functions (Musiolik and Markard 2011). These knowledge and valuation resource subsystems represent networks – both formal and informal – that involve joint activities directly linked to building innovation system resources. These resource subnetworks are like layers in the

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[3] We do note, however, that some policy network theory proposes the opposite relationship between network structure and the need for network-level competencies like trust and addressing complex problems. Specifically, Berardo and Scholz (2010) propose that when the challenges facing the network have low complexity and therefore require fewer resources and low-risk, then centralized, open-triangle structures prevail. As complexity increases and there is more of a need for creative solutions, transitive, closed-triangle structures prevail. This contrasting view represents the ongoing debate in network studies on the social processes represented by the classic open and closed triangle motifs.

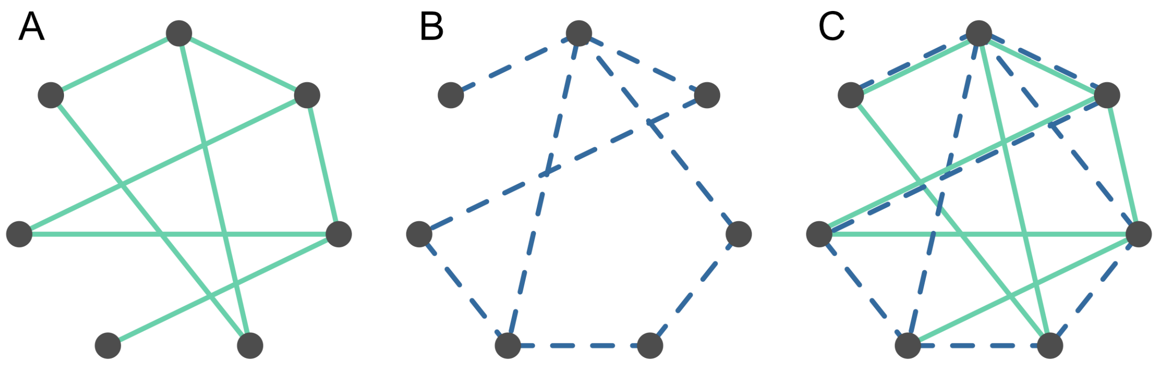

Figure 3.2: A) (left) A subsystem/network to address one kind of system resource deficit (e.g. knowledge development). B) (center) A subsystem to address a second kind of system resource deficit (e.g. market formation). C) (right) The combination of both resource subsystems, which make up a multi-functional innovation system network.

total innovation system network, where the structure of each builds the structure of the whole (Figure 3.2). We use these two resource subsystems – the knowledge and valuation subsystems – as cases for testing the resource-based theory.

> H1: Partner mode network structures, represented by closed triangles, will be more prevalent than intermediary mode network structures, represented by open triangles, when innovation subsystems have existing, decentralized resources

2.2.2 Actor composition based on institutional logic

Actor agency and institutional logics are central to innovation system formation (Kern 2015; Musiolik and Markard 2011). For example, "system builders" are prime movers who create cohesion and direction within an innovation system (Hellsmark and Jacobsson 2009; Musiolik et al. 2020). Similarly, "intermediary" actors come in several forms to help facilitate transitions (Kivimaa et al. 2019). However, there is still a limited understanding of how different actor types participate in the innovation system and their roles in building different system resources (Alphen et al. 2010; Binz, Truffer, and Coenen 2014; Hermans, Stuiver, et al. 2013; Lamers et al. 2017). Thus we turn to our second research question: What types of actors are most involved in the formation of innovation networks?

We rely on the multi-actor perspective as a guide to classifying actors and understanding their activity within different resource subsystems (Avelino and Wittmayer 2016).[4] This approach sets out four categories of actors: state (public agencies and researchers), market (private firms), communities (households, families), and the third-sector (non-profit organizations). Hybrid categories can also emerge at the intersection of these types, such as public-private partnerships. Among these categories, actors (which can be identified as individuals or as part of a broader organizational structure) are distinguished by their agency (e.g. a governmental researcher). In contrast, the institutions to which actors belong (e.g. public institution) do not have agency but rather they align with a particular "logic" (Avelino and Wittmayer 2016). For example, public agencies are guided by their social commitment, firms are guided by efficiency, and third-sector organizations are guided by a blend of these motivations. Similar concepts are described in the Triple Helix model's proposal that university, industry, and government each have their own selection pressures: novelty production, wealth creation, and normative control, respec-

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[4] We choose to focus on actor types rather than the idea of "system builders" (Musiolik et al. 2020) for three reasons. First, we argue that when and how an actor is classified as a system builder appears largely a matter of perspective. In line with challenges in multi-stakeholder assessment, classifying actors into bins such as key players "tends to identify the 'usual suspects' and there is a danger that this may lead to the under-representation of marginalised or powerless groups" (Reed et al. 2009). Second, system building is relational, and so instead of identifying system builders *before* carrying out our analysis, we can instead identify system builders based on the outcomes of our network analysis. Third, we argue that the line between strategic and emergent system formation is blurred. While system building is guided by individuals, it relies on the whole network, making the 'builder' versus 'other actor' distinction less important. We make this point further with regards to formal and informal networks in our case description (Section 2.3).

tively (Leydesdorff and Meyer 2006). These perspectives help guide our expectations of what kinds of actors we're likely to see involved in innovation resource subsystems and why.

We propose that there will be variation in the prevalence of different actor-types across the different resource subsystems (Figure 3.1C). Actors from non-profit sectors such as government agencies, public research institutions, and non-profit organizations are traditionally guided by social commitment (Avelino and Wittmayer 2016), and generation of pre-competitive public goods such as knowledge resources (King, Toole, and Fuglie 2012). Theory on strategic niche development reinforces this point given that governmental support is often considered important for protecting and nurturing niche innovation spaces before they are profitable (Smith and Raven 2012). Further, explorations of knowledge creation networks find that actors from universities and research institutes account for the vast majority of actors compared to those from for-profit groups (Alphen et al. 2010; Binz, Truffer, and Coenen 2014).

> H2a. Non-profit stakeholders (government, university, and organizations) are more active in the knowledge resource subsystem compared to other actors

On the other hand, for-profit actors typically engage in competitive and profitable activities (King, Toole, and Fuglie 2012), and so processes like resource acquisition and developing business relationships better align with their incentive structures. For example, research on innovation platforms finds that there is a diverse representation of groups in the knowledge development and diffusion stages, but this representation shifts towards a higher prevalence of private actors in the market formation stage (Lamers et al. 2017).

> H2b. For-profit stakeholders (companies) are more active in valuation re-

source subsystems compared to other actors

2.3. Case: Organic seed innovation system

We test our hypotheses about resource subsystem formation using the case of the organic seed system in the United States – a niche innovation system linked to the broader organic agriculture niche. Organic seed systems represent technological (and in some cases social) innovations for researching/breeding, producing, processing and selling seeds suitable for organic agricultural production (Almekinders and Louwaars 2002). Seed researchers develop and test new plant varieties (ideally those suitable for organic conditions, (Rohe et al. 2022)), seed producers grow crops under organic conditions to harvest and sell their seed, and seed processors and companies are the industries that process the seed and sell it to consumers, from hobby gardeners to large scale organic crop producers. Additionally, there are organizations and government agencies that play several of these roles, including research, education, seed saving, and certification. More details about the history of the organic seed system are described in Chapter 1 and Chapter 2, and several recent papers on the US and European contexts (Colley 2022; Sievers-Glotzbach et al. 2020; Tschersich et al. 2023).

The organic seed innovation system includes a variety of networks that serve different functional purposes, from seed exchange and knowledge diffusion to equipment rental and sales. These networks are a blend of both formal and informal networks. A formal network is an "organizational structure with clearly identifiable members where firms and other organizations come together to achieve common aims" (Musiolik, Markard, and Hekkert 2012) (1034). There are clear examples of such networks in the organic seed system, such as membership in a grower's association, contracting with a seed processor, and collaboration in joint research projects. There are also various informal networks, such as knowledge exchange with neighboring farmers and exchanging seed at seed swaps. The categorization of several other networks, however, is less clear; for example, subscription to a listserv, attending a conference, or renting equipment. All of these connections are ways that stakeholders innovate and shape the system, but membership can be transient (e.g. conference attendees), and whether this is strategic or emergent is hard to delineate (Musiolik et al. 2020).

Much of the IS network research has focused on formal networks (Célia Cholez and Marie-Benoît 2023; Musiolik et al. 2020). However, we include both formal and informal networks in this study for two reasons. First, the practical line between formal and informal networks is blurry. Formal networks may generate informal networks (Célia Cholez and Marie-Benoît 2023; Laurens Klerkx and Proctor 2013), informal exchanges may at some point become formalized, and indeed, informality has been found to have a stronger influence of beliefs and behaviors (Prell et al. 2010). Second, acknowledging the gradient of network (in)formality more fully represents the complexity of innovation systems, where emergent and strategic system formation are not mutually exclusive (Musiolik et al. 2020; Van de Ven 2005). Thus to capture the full range of relationships that help form a network in the organic seed systems, we consider the wide range of relationships that support different system resources.

3. Methods

3.1 Data collection

We identified organic seed system stakeholder populations first through comprehensive database creation of seed producers, companies, and researchers, followed by a snowball wave of survey sampling that helped us identify additional actors and relevant non-governmental organizations. Greater detail of this sampling process is in Chapter 2 (Section 3.1.1). In total, we identified a population of 756 stakeholders in the organic seed innovation system, summarized in Table 3.1. While setting boundaries around innovation systems is a core challenge to the field (Bergek et al. 2008), we believe this identification approach captures a wide range of both formal and informal actors across multiple innovation system functions.

We conducted a series of online surveys with the four groups of organic seed stakeholders – seed producers, companies, researchers (including academics and government agencies), and organizations – between 2020-2022. The surveys asked respondents about their role in the seed system, their perceived challenges and expertise, and perceptions on several issues salient in organic seed. Additionally, respondents were asked about the people or organizations that they seek and exchange information with, who they collaborate with on research, who they work with along the supply chain, including seed contracts, equipment rental, and sales, and who they source germplasm from for breeding and exchanging seed. Surveys were hosted on the Qualtrics survey platform and distributed over email. Each potential respondent was sent an initial email invitation with three reminders, spaced out every two to three weeks (Dillman, Smyth, and Christian 2014).

Out of those we surveyed, we have responses from 94 seed producers, 49 companies, 60 academic and governmental researchers, and 44 organizations for a combined response rate of 33% (247 of 756). The response rates for each actor-group are shared in Table 3.1, and a more extensive description of our sample's representativeness in Appendix C.

Table 3.1: Organic seed innovation system population, sample, and survey response rate by survey group

Survey group	Population (N)	Sample (n)	Response rate (%)
Researcher	117	60	51
Company	130	49	38
Organization	93	44	47
Producer	416	94	23
Total	756	247	33

3.2 Challenges and expertise as system resources

We measure the status of system resources using survey questions about challenges and expertise among actors in the organic seed innovation system. Surveys for seed producers and companies (including various supply chain actors like breeders, processors and retailers) asked the question: "How much have the following been a challenge to you in your work organic seed?" followed by a list of 28 production and business topics identified by experts in the Organic Seed Alliance. Surveys for seed researchers and organizations were provided the same list of topics, but instead asked: "To what extent do you have expertise/work with the following?"

Of the 28 topics presented to respondents, we select 18 that are relevant to knowledge and valuation resources and represent a unique issue (full list is available in Appendix C). Examples of knowledge-related topics include controlling weeds, managing climatic effects, and irrigation. Examples of valuation-related topics include developing infrastructure, sourcing appropriate equipment, and accessing land. Respondents scored their perceived challenges or expertise on a scale of 1 to 4. For challenges, the scale represented: no challenge (1), somewhat of a challenge (2), moderate challenge (3), and serious challenge (4). For expertise, the scale represented: no expertise/not my work (1), low expertise/rarely work on (2), moderate expertise/sometimes work on (3), and strong expertise/often work on (4). Based on these survey questions we are able to compare the challenges and expertise in the organic seed system and describe the dynamic of knowledge and valuation resources at the systems level. We also supplement these descriptive statistics with open-ended comments from the surveys.

3.3 Network construction

We constructed the innovation system network using the survey questions related to actors' connections. These connections were elicited using the "hybrid" network question approach (Henry, Lubell, and McCoy 2012). Using this approach, respondents were asked to list up to five to ten people or organizations (number varied with question) that they look to, work with, or source from across several seed-related contexts. For each name they wrote, respondents had the option to select the types of relationships. We match the different relationships to the functional and resource-based frameworks combined by Binz et al. (2016). The knowledge subsystem includes connections related to information acquisition and exchange, research partnerships, stakeholder involvement in projects, and academic collaborations. The valuation subsystem combines the resource mobilization and market formation functions, which includes seed acquisition, seed exchange, research funding, licensing agreements, contracts, renting, buying, and/or selling to/from. These ties are defined in Table 3.2. This survey-based method of network creation has benefits over methods that derive relationships from co-participation, as is common in other innovation network studies (Alphen et al. 2010; Binz, Truffer, and Coenen 2014; Hermans, Stuiver, et al. 2013). First, this method does not rely on the assumption that actors who attend the same forum or are members of the same organization are necessarily in collaboration. Instead, this approach allows connections to be defined based on actors' own

Table 3.2: Operationalization of resource-based innovation subsystems based on relationship types

Resource subsystems	Functions	Types of relationships
Knowledge	Knowledge creation	Information acquisition and exchange, Research partnerships, stakeholder project involvement, and academic collaborations
Valuation	Resource mobilization	Seed acquisition, seed exchange, research funding
	Market formation	Licensing agreements, contracts, rent, buy, and/or sell to/from

perceptions of a relationship. Second, there are challenges to analyzing two-mode data (e.g. actor-to-project), or projections of two-mode data, with some inferential network methods (Jasny 2012), which we bypass by collecting one-mode data (e.g. actor-to-actor). However, there are limits to our approach. First, networks defined by survey responses will be incomplete, given the commonly low survey response rates. Second, survey network collection is cross-sectional and so we cannot speak to how the network evolves without repeating this data collection process.

The innovation system network includes a total of 1908 ties (1208 when un-weighted) between 645 uniquely identifiable actors. Based on data from the survey and supplementary seed stakeholder databases, we added actor-type and geographic attributes to each stakeholder in our network. The initial actor-types based on our surveys include producers, companies, non-governmental organizations, and researchers. We divide the actors in the research category into government agencies and public universities because we argue that university researchers have their own institutional logic (Leydesdorff and Meyer 2006). Aligning these groups with the multi-actor perspective (Avelino and Wittmayer 2016), companies represent firms, organizations represent the third-sector, and government researchers represent the state. Producers are a hybrid of firm and community logics, as their occupation is often linked to their identity, place, and a particular value set (Thompson, Reimer, and Prokopy 2015). Likewise, universities are a hybrid of state of third-sector logic. We also include the geographic location and spatial scale in which a particular actor is based (for more information see Chapter 2).

3.4 Analytical approach: ERGMs

To test how structural motifs and actor composition vary across seed innovation subsystems, we employ two Exponential Random Graph Models (ERGMs) (Lusher, Koskinen, and Robins 2012). ERGMs are an inferential network analysis method that estimate the likelihood that a network tie will form based on endogenous and exogenous predictors (Robins, Lewis, and Wang 2012). Endogenous predictors are the structural features of the network itself, such as the number of connections and actors, open and closed triangle formations, among many others. Exogenous predictors are features of the actors in the network – referred to in network terminology as "nodes" – which in this analysis include the actor types and their geographic region and scale. An ERGM estimates the likelihood that these features influence tie formation in the observed network by comparing it to thousands of simulated graphs that have the same structural parameters as those specified in the model.

The ERGMs we fit in this paper include five endogenous structural terms and six exogenous node attributes (Table 3.3). Of focus for our first hypothesis are two of the endogenous structural terms. These include a structural parameter for a node's degree (specified with geometric weighting, "gwdegree"), which represents the likelihood of an actor forming a tie given the number of ties it already has. In other words, the likelihood of an *additional* tie forming (Levy and Lubell 2018). Based on our first hypothesis, we expect a positive value of this parameter, which indicates a tendency away from centralization and more open triangles (Levy 2016).[5] Second, we include a structural parameter for triadic closure (specified as geometrically weighted edgewise shared partners, "gwesp"). This parameter represents the likelihood of a connection to close a triangle, meaning to connect two actors who share a connection to a third actor (Scott and Thomas 2015). We expect a positive value of this parameter, which indicates a tendency of the network to have more closed triangles.

Of focus for our second hypothesis is the network's actor composition, an exogenous node attribute. Each node in the network is associated with an actor-type, and the relative activity of each actor type (i.e. propensity for forming a tie) is compared against a baseline. In our analysis we set seed producers as the comparison group, against which a parameter value is estimated for each actor type representing their likelihood of forming a tie. These estimations help us better understand what kinds of groups are more or less active across the networks. Based on our second hypothesis, we expect positive parameter values for non-profit actors in the knowledge subsystem and a positive parameter value for for-profit actors in the valuation subsystem.

The remaining eight terms in the model are controls. The geographic controls, regional homophily and geographic scale, account for the within-region affinity that is prominent in the organic seed network and the relative prominence of national and international actors (Chapter 2). The structural and design controls account for the influence of the survey sampling method on the shape of the network, as well as how connections in one network influence the connections in another via multi-functional spillover (e.g. horizontal coupling, see Chapter 2). We estimate an ERGM for each of the two resource subsystems in order to identify the variables that most influence network formation. We use the stat-

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[5] Note that this parameter is often misinterpreted in studies that use ERGMs and we encourage readers with further interest to explore in the following resource: (Levy et al. 2016)

Table 3.3: ERGM parameters and their associated concepts and hypotheses

Parameter group	Parameter	ERGM term	Concept	Hypothesis
Network structure	Anti-centralization	gwdegree	Lower centralization	H1: Low centralization (positive anti-centralization coefficient)
	Triadic closure	gwesp	More closed triangles	H1: High triadic closure (positive parameter coefficient)
Actor composition	Actor-type	nodefactor	Actor's likelihood of forming a tie based on role	H2a: Non-profit actors: positive coefficient for knowledge subsystem H2b: For-profit actors: positive coefficient for valuation subsystem
Spatial controls	Regional homophily	nodematch	Affinity for within-region linkages	
	Geographic scale	nodefactor	Activity of national/international vs. regional actors	
Structural and design controls	Survey non-respondent	nodefactor	Likelihood of non-respondent to form tie	
	Inf zero for non-respondent	offset(edgecov)	Offset non-surveyed actors to create ties	
	N respondents in organization	nodecov	Increase of tie likelihood with multiple respondents	
	N generic connections	nodecov	Number of generic respondents	
	Activity in other subnetwork	edgecov	Multi-functional spillover	
	Edges	edges	Likelihood of forming a tie based on N edges	

net (Krivitsky et al. 2022) software package. All analysis was conducted using R statistical software (Team 2023) and code is available at github.com/liza-wood/osisn_processes. Details on model building and selection are available in Appendix C.

4. Results

4.1 Organic seed system resource deficits

The organic seed system has been developing now for over twenty years (Hubbard, Zystro, and Wood 2022), but it still faces several challenges as it stabilizes. In this section we summarize the state of the system's knowledge and valuation resources based on challenges and expertise reported by seed stakeholders.

The greatest challenges for producers and companies in the organic seed system relate to knowledge deficits on the technical (generally agronomic) strategies for organic seed production. Controlling weeds, estimating and achieving adequate seed yields, and managing climate effects are among the most serious challenges facing seed producers and firms along the value chain (Figure 3.1A). Survey respondents provided open-ended comments to reinforce these points, for example, "Weed control is a huge challenge and effect [sic] seed quality and yield." ; "Constantly changing climate; Rodents and other pests for roots and legumes; Cabbage family pest Harlequin beetle". Challenges related to valuation resources are slightly less serious, though actors do face issues such as developing infrastructure, accessing labor, production costs, and sourcing appropriate equipment (Figure 3.1B). One respondent noted their need for experienced labor by commenting that "I would and could expand the seed operation with more folks on board but not alone as it is now."

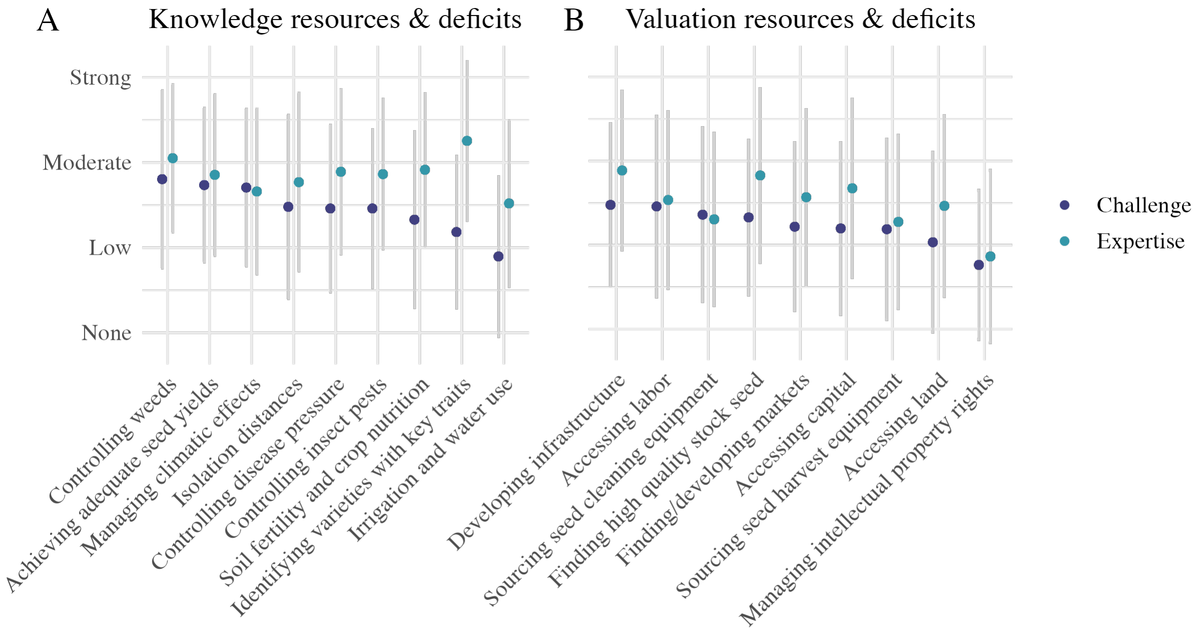

Figure 3.3: Ratings of challenges (purple) and expertise (blue) for topics related to A) Knowledge resources and B) valuation resources. Points represent the mean score from respondents ratings (challenge n=144, expertise n=104) and gray bars represent error.

The average rating of knowledge-based challenges among respondents is 2.5 (between low and moderate challenge), compared to the average rating of 2.2 for valuation-based challenges. Though the difference is small, a comparison of means using a Welch Two Sample t-test between the two groupings finds a significant difference ($p < 0.001$), suggesting that there is a significantly larger resource deficit for knowledge than valuation resources. Though the challenges experienced by stakeholders point to moderate resource deficits in the organic seed system, there are also expertise in the network that address these same topics. Expertise is highest (rated about moderate) on knowledge-related topics, such as identifying key traits, controlling weeds, soil fertility, and disease pressure. There is also some (low to moderate) expertise available on valuation topics like developing infrastructure, finding high quality seed stock, and accessing capital.

The average rating of agronomic knowledge-based expertise among respondents is 2.9

(moderate expertise), compared to the average rating of 2.5 for valuation-based challenges. Again, though the difference is small, a comparison of means between the two groupings finds a significant difference ($p < 0.001$), suggesting that there is a significantly higher average expertise for knowledge than valuation topics.

Comparing challenges and expertise to assess system resources, we generally see that the strength of expertise by researchers and organizations is higher than the magnitude of challenges reported by seed producers and companies. On average, expertise related to knowledge resources score 0.4 points higher than challenges related to knowledge resources, and only one topic – managing climatic effects – has lower expertise than challenges. Similarly, average expertise related to valuation resources score 0.3 points higher than challenges related to valuation resources, and again only one topic – sourcing seed cleaning equipment – has lower expertise than challenges. Overall, the summaries suggest that the organic seed system has the resources it needs to address its challenges.

What we cannot say using these descriptive summaries, however, is how well the supply and demand across these resources align in the network. Some respondents report satisfaction with the resources available to them: "A few good books and a few field days under our belt and you can do a lot of seed saving." In other cases, however, the quality and relevance of the expertise in the system may be perceived as inadequate by the stakeholders facing the challenges. For example, despite there being considerable expertise in controlling disease pressure among survey respondents, one seed producer remarks: "MORE OPEN-SOURCE info on Pertinent seed-born diseases!! Easily searchable interface giving a list of possible diagnosis and possible protocols." Furthermore, there are some producers that feel that existing resources are not relevant for their production context. For example, respondents note: "Hard to find people with sufficient knowledge and familiarity with the crops I grow" and "I feel like the [Southeast] has its own set of growing issues which are not always researched. They especially complicate seed growing.”

Based on the data we have on challenges and expertise across resources in the organic seed system, we propose that both the knowledge and valuation subsystems have resources that are existent but distributed. Situating Hypothesis 1 in this case context, we expect both subsystems to be built around closed triangles (i.e. partner mode) based on this resource availability. Between the two subsystems, however, we observe that the availability of valuation resource expertise is lower than knowledge resource expertise. As a result, we expect the valuation subsystem to have fewer closed triangles relative to the knowledge subsystem, suggesting a tendency towards an intermediary mode to help address resource deficits.

4.2 Network descriptives

The organic seed innovation system identified through our survey methods includes 645 stakeholders forming 1908 connections to one another. Across the two resource subsystems, the knowledge subsystem is larger compared to the valuation subsystem, where 522 actors account for 1106 ties compared to 418 actors accounting for 802 ties, summarized in Table 3.4. On average, an actor in the whole innovation system network and its two subsystems will have 5.92, 4.24, and 3.84 connections, respectively. The transitivity of each network, which summarizes the clustering of nodes into triangles, is low and generally decreases with network size. Last, the degree centralization of each network, which summarizes the extent to which the connections in the graph are organized around central nodes, is highest in the knowledge subnetwork and lowest in the valuation subnetwork. Across the different actor types, companies and organizations each account for nearly a third of the whole innovation system network, producers a fifth, and university exten-

Table 3.4: Descriptive summaries of the innovation system network and resource subsystems

	Whole system	Knowledge	Valuation
Actors	645	522	418
Connections	1908	1106	802
Avg. # connections	5.92	4.24	3.84
Transitivity	0.09	0.09	0.06
Centralization	0.1	0.12	0.08
Producers	124 (19%)	100 (19%)	91 (22%)
Company	209 (32%)	147 (28%)	178 (43%)
Organization	190 (29%)	171 (33%)	86 (21%)
University & extension	73 (11%)	73 (14%)	33 (8%)
Government	49 (8%)	31 (6%)	30 (7%)

sion and government actors together account for the remaining fifth. Representations vary across the resource subsystems, however. Relative to the whole system, for-profit actors like producers and companies account for a higher percentage in the valuation subnetwork, and non-profit actors like organizations and university researchers represent a greater fraction of the nodes in the knowledge subnetwork.

The seed innovation system network and its two resource subsystems are visualized in Figure 3.4. In both cases, the subsystems are almost entirely connected as one component, meaning nearly every node can connect to other nodes by different "paths." Across the subsystems there is decently strong correlation (0.41), suggesting that most actors use connections for multiple purposes that support both knowledge and valuation resources. These structural summaries provide an overview of the organic seed network, but we cannot use them to make inferences about what drives these structures, nor generalize them to speak more broadly about the tendencies of structural formation across different relationships. In the next section, we turn to the results of our structurally explicit network analysis to elaborate on the relationship between structure and resource needs

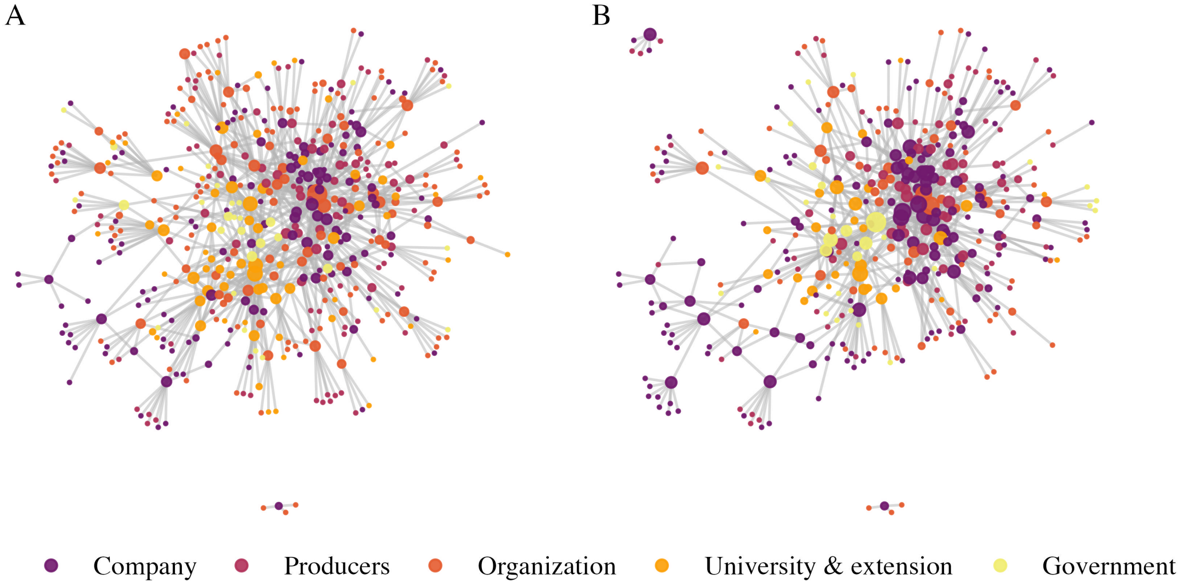

Figure 3.4: A) Knowledge and B) valuation resource subsystems of the organic seed innovation system. Circles in the graph represent actors/organizations and lines represent connections based on the different relationships within each subsystem. Nodes are sized by their relative popularity in the figure (the larger, the greater number of ties they have). Nodes are colored based on their role (outlined in the legend), with the color gradient ranging from more private (darker) to more public (lighter).

in innovation systems.

4.3 Network inferences with ERGMs

We address our hypotheses about the structure and composition of the organic seed innovation subsystems using results from the Exponential Random Graph Models. An ERGM estimates the likelihood of network tie formation, providing statistically supported explanations of why network structures form. Model results presented in Figure 3.5 show coefficient estimates and their confidence intervals as log-odds. When reading log-odds, a basic intuition is that values less than zero represent lower probabilities of forming a tie and values greater than zero represent higher probabilities of forming a tie. To interpret specific statistics throughout the text, we transform the log-odds into odds and evaluate the difference between the coefficient value and one in order to describe the likelihood of a tie as a percentage (Scott and Thomas 2015; Ulibarri and Scott 2017). A table of full model results is available in Appendix C.

4.3.1 Resource subsystem structure

In this section we present results related to our first hypothesis: Closed triangles/partner mode network structures will be more prevalent in innovation resource subsystems that have existing, decentralized resources. As described in Section 4.1, the organic seed innovation system has existing, distributed knowledge and valuation resources. Based on these conditions, we expect that both subsystems will be built up by closed triangles, measured by a positive triadic closure parameter, rather than open triangles measured by a negative de-centralization parameter. Between the two subsystems, however, we expect the valuation subsystem to have fewer closed triangle structures, as it tends toward the more centralized, intermediary mode to address its deficits.

The variables relevant to this hypothesis are anti-centralization and triadic closure (Figure 3.5). For the anti-centralization coefficients, we observe positive, significant, and large estimates for both resource subsystems (knowledge: 5.2, SE: 0.52 ; valuation: 4.38, SE: 0.5). Similarly, for the triadic closure parameter we observe positive and significant coefficient estimates for both resource subsystems (knowledge: 0.73, SE: 0.05 ; valuation: 0.43, SE: 0.07).

On the whole, these structural results align with what we expected in our first hypothesis. These resource subsystems are relying on the partner mode of system resource formation through closed triangle structures to connect actors to available resources. For example, based on the triadic closure term, the odds of a tie between two actors with a shared partner are 102% greater than the odds of a tie between two actors with no shared partners in the knowledge subnetwork. And based on the anti-centralization term, the odds of an actor forming a tie with another actor that already has two connections in the valuation subsystem are 32% lower than the odds of that same actor forming a tie with another actor that only has one existing connection. Put more simply, rather than forming open triangle structure with a central, coordinating actor, seed system stakeholders are building more diffuse relationships for cooperative, partnered relationships. When comparing the structures of the knowledge and valuation subsystems to one another, we observe some variation that lends further support for the resource-based theory. The models estimate that the knowledge subsystem, which has more expertise (resources) than the valuation subsystem, has more closed triangles and lower centralization (higher anti-centralization) than the valuation subsystem. While the odds of a tie forming between two actors with a shared partner are 102% greater than the odds of a tie between two actors with no shared partners in the knowledge subsystem, these odds decrease to 51% in the valuation subsystem. Likewise, actors in the knowledge subsystem are 37%

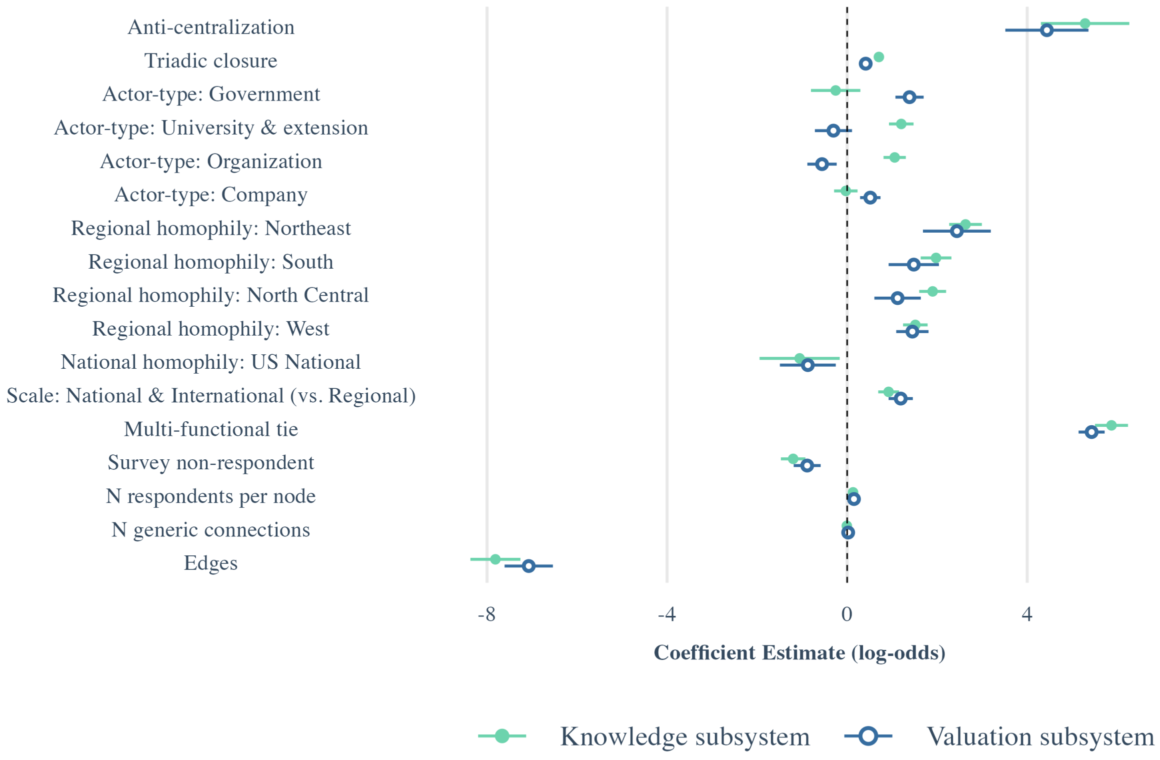

Figure 3.5: Coefficient plot for the ERGMs of the knowledge and valuation subsystems. Each point represents the value of the coefficient estimate (reported as log-odds) and bars represent the confidence intervals surrounding each estimate.

less likely to form a tie with a popular, coordinating actor, in contrast from the 32% lower likelihood in the valuation subnetwork. In short, the knowledge subsystem structure suggests a slightly stronger reliance on partner mode of network building compared to the valuation subsystem.

4.3.2 Resource subsystem composition

In this section we present results related to our second set of hypotheses, that non-profit stakeholders are more active in knowledge subsystems (H2a), while for-profit stakeholders are more active in valuation subsystems (H2b). The "actor-type" variables in Figure 3.5 represent the likelihood of each actor-type forming a tie compared to our baseline group of seed producers.

For the knowledge subsystem, university and organization actors are significantly more active than the baseline, with coefficient estimates of 1.12 (SE 0.15) and 0.96 (SE 0.13) respectively. Converting these estimates into odds, the odds of these actors' forming a tie is 233% (university) and 187% (organization) greater than the odds of seed producers forming a tie in the knowledge subsystem. Neither government nor company actors, however, are particularly active in knowledge subsystems. These results partially support H2a, given the strong activity by university and organizational actors, but the average activity levels of government actors did not align with our expectations.

For the valuation subsystem, both companies and government actors are significantly more active than the baseline, with coefficient estimates of 0.52 (SE 0.12) and 1.42 (SE 0.18) respectively. In other words, the odds of these actors forming a tie is 67% (companies) and 300% (governments) greater than the odds of seed producers. On the flip side, organizations are significantly less likely to participate in these networks, with a coefficient estimate of -0.5 (SE 0.16). These results partially support H2b, given the strong activity by companies, however the prominent role of government was not as expected.

5. Discussion

5.1 Conditions for innovation system formation

Our results support the resource-based theory that the existence (or deficit) of resources help predict the kinds of network structures that will form within an innovation system (Musiolik et al. 2020). We find that when resources are existent but diffuse, the partner mode of network building – operationalized as closed triangles in social network and network governance literature (Provan and Kenis 2008; Rudnick et al. 2019) – is more likely to structure the network. This is true across both the knowledge and valuation resource subsystems related to organic seed, which represent the multiple functionalities of network structure within an innovation system. This research is among the first to empirically test conditions predicting network structure in the innovation systems literature (Célia Cholez and Marie-Benoît 2023; Rohe and Mattes 2022).

We draw on social network and network governance fields to help operationalize the resource-based theory and contextualize our results. We see strong theoretical similarities between the resource-based theory and the theory of network governance, which identifies the need for network-level resources as an important determining factor in the choice of network structure (Lubell, Jasny, and Hastings 2017; Provan and Kenis 2008). When there are network-level resources required, such as building trust and reputation, or coordinating actors to create something new outside of the existing expertise, the intermediary mode of open triangles with a central coordinator is more useful. On the other hand, in the organic seed network where the task is about connecting existing resources and creating complementary alliances, the partner-mode of closed triangles is more useful.

Connecting innovation system studies to the social network and network governance fields opens up new lines of questioning related to the conditions of network formation. For example, there are likely other system features that predict network structure, such as size, trust, goal consensus, task complexity, level of uncertainty, and customization (Jones, Hesterly, and Borgatti 1997; Provan and Kenis 2008). Some of these have been theorized and explored in innovation systems research, such as the customization of products affecting structure across spatial scales (Binz and Truffer 2017), and how trust and network size change over time (Hermans, Van Apeldoorn, et al. 2013). Still, considerably more research is needed to build out and test these conditions in the context of innovation systems. Further, the methods for testing these conditions need to become more consistent across the field to support comparable results. We propose quantitative and inferential network analyses, including methods like conditional uniform graph tests, exponential random graph models, and autologistic actor attribute models (Robins, Lewis, and Wang 2012), as approaches for rigorously testing network building theory (Scott and Ulibarri 2019).

Finally, it is of note that the structure of the organic seed network is quite different from most networks studied in the governance literature, where it is common to find highly centralized networks with dominant intermediary structures (Berardo and Lubell 2016; Scott and Thomas 2015). Beyond the explanation of resource variation, one reason for this pronounced difference observed in the organic seed network may have to do with scale (Hileman and Lubell 2018), given that the national-level focus in this paper is higher than most governance network studies. However, when we break down the national-level network into regional sub-networks to explore the effect of scale, we see little change in the prevalence of open and closed triangle motifs (Appendix C). A second factor may have to do with operationalization of the network connections. Innovation system networks are unique from governance networks in that they include a much wider set of activities – not only collaboration around a shared challenge, but also knowledge development, resource mobilization, and market formation, to name a few. The relatively narrow functional purpose of some governance networks may lend themselves to centralization more so that innovation networks.

5.2 Actor composition aligns with institutional logics in the niche phase

While resource-based needs shape the overall network structure of the organic seed resource subsystems, we find that actors' institutional logics also shape relationship-building activity. Our results largely support the idea of institutional logics defined by the multi-actor perspective (Avelino and Wittmayer 2016). We find that non-profit actors like organizations and universities are significantly more active in the knowledge resource subsystem, while for-profit companies are more active in the valuation resource subsystem. These results fit with the understanding that there are pre-competitive (knowledge creation) and competitive (knowledge exploitation and value creation) divisions among public/non-profit and private/for-profit actors (King, Toole, and Fuglie 2012). These results help us better understand what it means to be a system builder (Musiolik et al. 2020), as system builder profiles likely change based on the kinds of resources that are being generated (Leydesdorff and Meyer 2006). Activity levels are likely to be higher among actor-types whose incentive structures align with the system resources being created in the network.

Alignment between institutional logic and resource subsystems met our expectations for all of the actor types except government. Rather than fitting cleanly into the role of public actor-types with a pre-competitive logic, governments played a blended role. Governmental actors were considerably more active than the baseline in the valuation subsystem, but not the knowledge subsystem. Though these results defy the more traditional logics of government (Avelino and Wittmayer 2016; Leydesdorff and Meyer 2006), they make sense in the context of a niche innovation system. Because niches are often not yet competitive in their own right, the government can play a nurturing role to support traditionally private functions (Smith and Raven 2012). For instance, the breeding material shared by the government's national and regional repositories are a central contributor to the supply chain, providing important genetic inputs for R&D and plant variety development early in the innovation process.

These findings advance our understanding of actor agency by mapping system-building motivations to actors' institutional logics. While actor composition has been of interest to innovation systems, rarely has this work been able to generalize findings about certain types of actors leading particular functions (Lamers et al. 2017). Understanding not only *what* structures are forming, but also *who* is forming those structures can help policymakers identify what kinds of stakeholders to support for different types of innovation system development.

5.3 Limitations

The theoretical and methodological contributions of this paper are certainly not without limitations. First, we took the partner and intermediary mode concepts from resource-based theory and translated them into the social network motifs. In this there is room for interpretive error. We relied on the intermediary mode description from Musiolik et al. where “a system builder coordinates activities in a network of collaborators to develop new, intermediate organizational structures.” (2020, 10) We believe this aligns best with Provan and Kenis’s (2008) description of lead and network administrative organizations for governance, which map onto open triangle structures. However, there is room for interpretation. Specifically, the intermediary mode is also described as “risk sharing”, where “system resource build-up is demanding” (Musiolik et al. 2020). Other theoretical perspectives, such as the risk hypothesis in policy network literature (Berardo and Scholz 2010), associate the social processes best suited for these risk-sharing dynamics with closed triangles.

Furthermore, operationalization and measuring resource existence and distribution in the organic seed system was difficult. As mentioned in Section 4.1, we are limited in assessing the quality of the expertise, and in understanding how actors with different challenges and expertise align in the network. So while we conclude that resources do exist across the system, we recognize that these resources may not be evident, accessible, or relevant to the actors who need it. Future studies should do more to clarify how to define resource availability and deficits in order to strengthen testing of the resource-based theory.

6. Conclusion

This paper seeks to understand the conditions predicting innovation system network formation and actor composition. We test existing theories about resource-based innovation networks (Musiolik et al. 2020) and institutional logics (Avelino and Wittmayer 2016) by connecting to social network theory and methods (Provan and Kenis 2008; Robins, Lewis, and Wang 2012). We use the case of the organic seed innovation system, which we divide into two resource subsystems representing knowledge and valuation functions, both of which have existing but dispersed resources. Exponential Random Graph Modeling helps us statistically test the likelihood of tie formation to describe different network building processes and relative actor involvement. These models show support for the idea that resource constellations are important conditions shaping network structure. Additionally, we find that different actors' activity in resource subsystems depends on their incentive structure – public actors generally are engaged in knowledge resource building which private actors are generally more engaged in building valuation resource subsystems.

Understanding the processes by which innovation systems are formed is the first step towards improving system performance (Musiolik, Markard, and Hekkert 2012). This is especially important for informing policymakers about what types of network structuring modes are most relevant given a system's state of resources, and what types of actors are more or less likely to be active participants and leaders in these networks. In organic seed, for example, rather than needing new intermediary structures, the existing network ought to help identify actors with complementary resources for building cooperative relationships. Additionally, at this stage in the niche's development, policies should recognize the important role of government-backed resources like germplasm, and continue to support the provision of these public goods that support the niche supply chain (Alliance 2022). Altogether, these findings can help both researchers and policymakers better understand the circumstances under which certain system building strategies should be put into place.

Appendix A

Model selection and fit

Table A.1: Model comparison results

	Model 1		Model 2		Model 3		Model 4		Model 5	
Term	Mean	SE	Mean	SE	Mean	SE	Mean	SE	Mean	SE
Barrier: Organic availability					0.242	0.001	0.173	0.001	0.171	0.001
Barrier: Undesirable traits					0.105	0.001	0.124	0.001	0.121	0.001
Barrier: Buyer requirements					0.092	0.001	0.126	0.001	0.121	0.001
Barrier: Insufficient quantity					0.028	0.001	0.018	0.001	0.016	0.001
Year: 2015 (vs. 2010)	-0.371	0.002					-0.19	0.002	-0.175	0.002
Year: 2020 (vs. 2010)	-0.413	0.002					-0.309	0.002	-0.316	0.002
Values organic seed			-0.27	0.001	-0.202	0.001	-0.202	0.001	-0.200	0.001
Farm size (acres)			0.072	0.001	0.029	0.001	0.106	0.001	0.118	0.001
Crop diversity			-0.035	0.001	-0.064	0.001	-0.071	0.001	-0.068	0.001
Seed saved or traded (%)									-0.095	0.001
Certifiers request organic seed use									0.038	0.001
Forage crops (vs. Field)	0.82	0.002					0.932	0.002	0.903	0.002
Vegetable crops (vs. Field)	0.186	0.002					0.286	0.002	0.248	0.002
Western region (vs. North Central)	0.439	0.002					0.3	0.002	0.338	0.002
Northeastern region (vs. North Central)	0.325	0.002					0.25	0.002	0.249	0.002
Southern region (vs. North Central)	0.252	0.003					0.116	0.003	0.122	0.003
(Intercept)	-0.595	0.002	-0.455	0.001	-0.466	0.001	-0.702	0.002	-0.701	0.002

Table A.2: Goodness of fit across models

Model	WAIC	Maximum Likelihood	CPO
Model 1	-4310	2114	1.23
Model 2	-4247	2100	1.21
Model 3	-4354	2130	1.24
Model 4	-4478	2157	1.28
Model 5	-4484	2148	1.28

Full model results

Table A.3: Full model results

Term	Mean estimate	Standard error
Barrier: Organic availability	0.171	0.001
Barrier: Undesirable traits	0.121	0.001
Barrier: Buyer requirements	0.121	0.001
Barrier: Insufficient quantity	0.016	0.001
Year: 2015 (vs. 2010)	-0.175	0.002
Year: 2020 (vs. 2010)	-0.316	0.002
Values organic seed	-0.200	0.001
Farm size (acres)	0.118	0.001
Crop diversity	-0.068	0.001
Seed saved or traded (%)	-0.095	0.001
Certifiers request organic seed use	0.038	0.001
Forage crops (vs. Field)	0.903	0.002
Vegetable crops (vs. Field)	0.248	0.002
Western region (vs. North Central)	0.338	0.002
Northeastern region (vs. North Central)	0.249	0.002
Southern region (vs. North Central)	0.122	0.003
(Intercept)	-0.701	0.002

Predicted conventional seed use

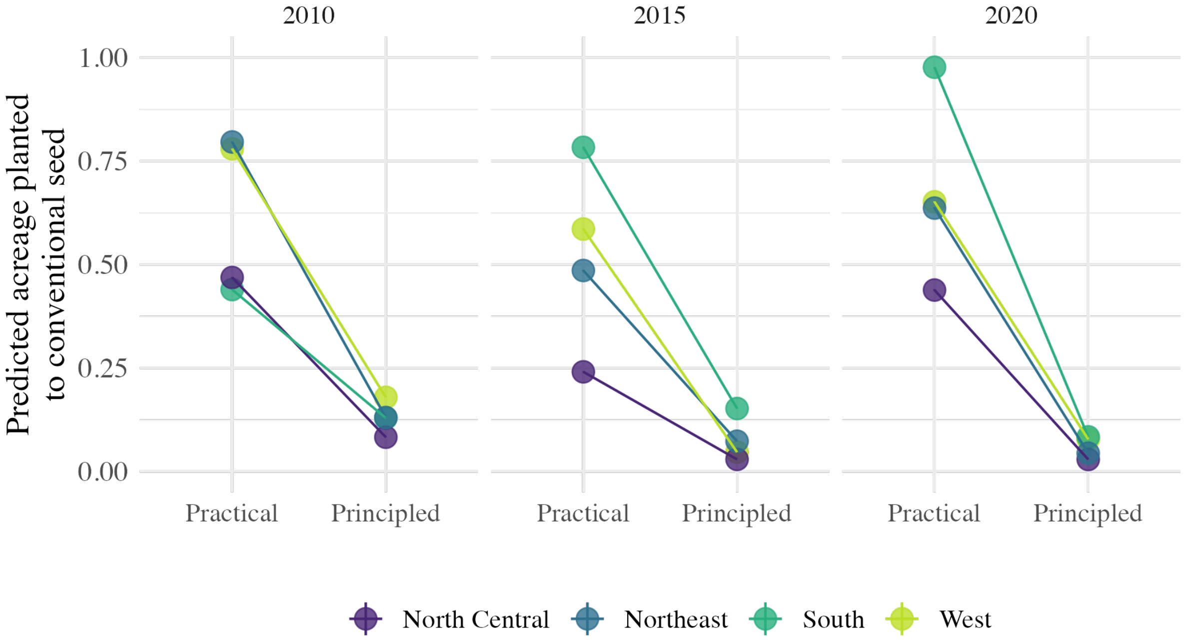

Figure A.1: Predicted conventional seed use for field crop growers of two farmer profiles.

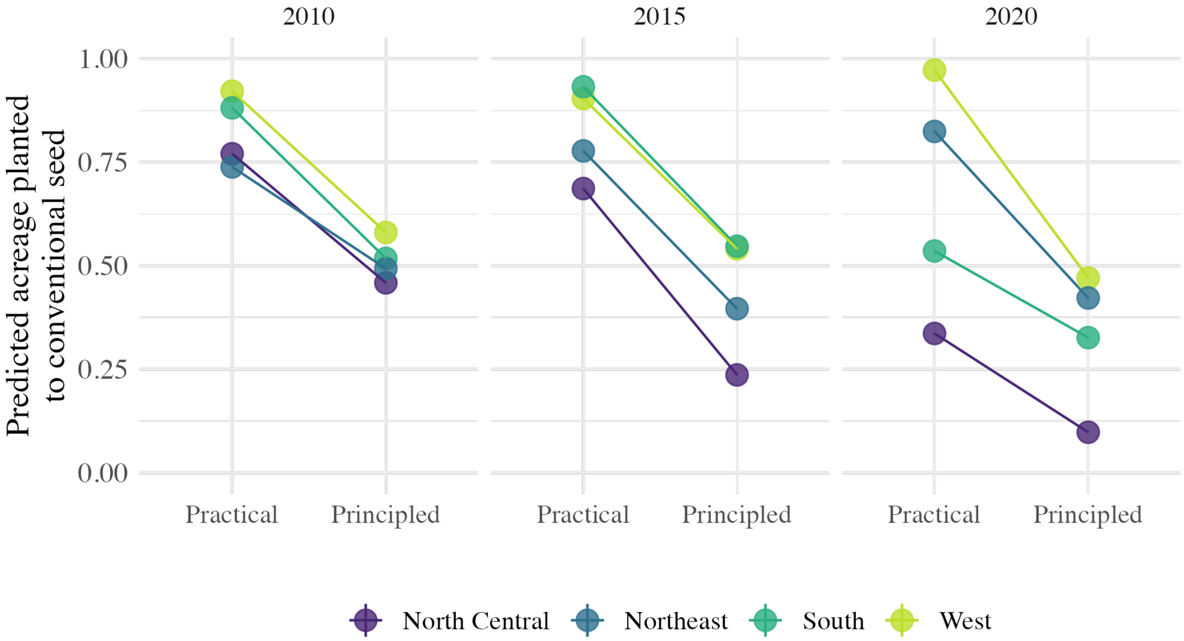

Figure A.2: Predicted conventional seed use for forage crop growers of two farmer profiles.

Appendix B

Selecting spatial terms

We explore space's influence on tie formation by comparing the USDA SARE regional homophily model with two other spatial models.

First, we test the spatial relationship of actors based on geodesic distances between one actor and another, rather than categorical spatial boundaries. This allows us to better understand whether within-region homophily is merely a matter of convenience (e.g. *I get information from my neighbor because it is easier*), rather than related to spatial embeddedness of the innovation. Actors for whom we don't have exact coordinates (154 of 645, 24%) are assigned the mean geodesic distance. Our model in Table B.1 shows a significant negative relationship between distances and likelihood of connection, suggesting that connections are not made only from convenience of distance. Instead, the results from the regional homophily model suggest that actors seek others who have relevance to the resources they need (not just convenience), but still in the regional context that they need it.

Table B.1: Full model results: Geodesic distance covariate

	Knowledge subsystem		Valuation subsystem	
Term	Estimate	SE	Estimate	SE
Spatial distance (log)	-0.071	0.030	0.077	0.040
Scale: National (vs. Regional)	-0.053	0.095	0.626	0.052
Other subsystem structure	5.331	0.159	0.343	0.354
Anti-centralization	4.946	0.495	3.681	0.394
Triadic closure	0.810	0.049	0.802	0.044
Edges	-4.799	0.431	-6.287	0.577
Survey non-respondent	-1.150	0.130	-1.076	0.106
N respondents per node	0.269	0.030	0.107	0.027
N generic connections	-0.080	0.014	0.026	0.006
Fixed -Inf	-Inf	0.000	-Inf	0.000

Second, we run the model using 12 Plant Hardiness Zones (PHZ) outlined by the USDA, rather than the four administrative regions of SARE. These PHZs help zoom in on more specific similarities across space regarding growing needs. Because we do not have PHZs for Canada we assign Canadian nodes to the nearest USDA PHZ. Actors for whom we cannot assign a PHZ are given an 'other' category. Similar to the four administrative regions, we see also homophily within the PHZs (Table B.2).

Table B.2: Full model results: Plant Hardiness Zones (PHZ)

	Knowledge subsystem		Valuation subsystem	
Term	Estimate	SE	Estimate	SE
PHZ homophily: Zone 3	3.462	0.909	2.394	0.762
PHZ homophily: Zone 4	1.720	0.230	1.093	0.173
PHZ homophily: Zone 5	1.465	0.171	0.639	0.207
PHZ homophily: Zone 6	0.919	0.187	0.876	0.158
PHZ homophily: Zone 7	1.220	0.248	1.252	0.226
PHZ homophily: Zone 8	0.985	0.155	1.246	0.128
PHZ homophily: Zone 9	1.239	0.287	0.665	0.375
PHZ homophily: Zone 10	1.672	0.865	2.269	0.375
Scale: National (vs. Regional)	-0.030	0.095	0.662	0.073
Other subsystem structure	5.130	0.177	0.519	0.457
Anti-centralization	4.975	0.477	3.676	0.428
Triadic closure	0.795	0.050	0.715	0.057
Edges	-6.172	0.137	-5.459	0.140
Survey non-respondent	-1.158	0.140	-1.193	0.117
N respondents per node	0.286	0.023	0.146	0.037
N generic connections	-0.078	0.017	0.030	0.011
Fixed -Inf	-Inf	0.000	-Inf	0.000

We compare the model fit of these three approaches (Table B.3), and see that the best fit is based on the four-region model.

Table B.3: Spatial models comparison

	Knowledge subsystem		Valuation subsystem	
Model	BIC	AIC	BIC	AIC
Geodesic distance	6154	6066	6573	6488
Plant Hardizess Zones	6065	5908	6553	6403
SARE Regions	5832	5704	6363	6241

Defining actors' spatial scales

We assign actors' spatial scales based on the following decision criteria. First, university researchers and producers are all considered sub-national/regional actors based on the fixed nature of their organizations. Organizations (non-profit/non-governmental) were asked to self-identity, in surveys, the scale at which they operated. These responses were checked against the scope of the organization's mission listed on their webpages. Governmental actors were identified as national if they worked for a federal office. And companies were grouped into scales based on self-description on webpages, checked against their sales revenue. First, we looked up a company see how they self-described and marketed themselves on company webpages. Second, we looked up each company's sales revenues from 2022 using the D&B Hoovers database, which helped us validate the operational scale of the company. Figure B.1 shows the percent (x axis) and total count (in-figure text) of how scales are represented across different actor groups.

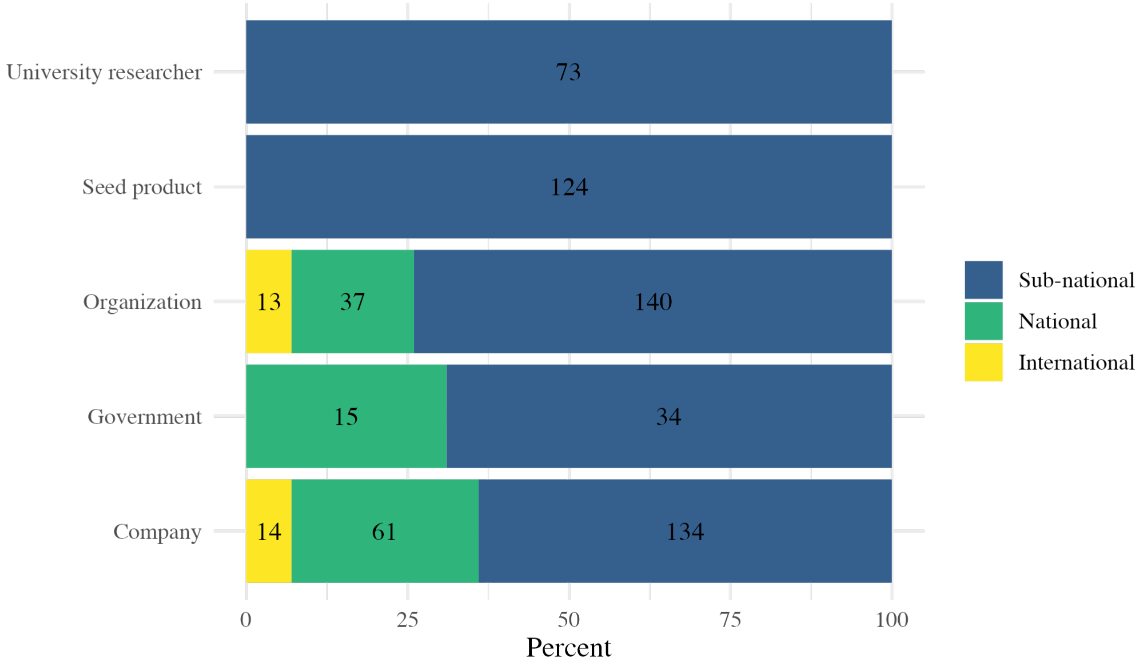

Figure B.1: Scales of operation by actor-types. Numbers represent counts

Full model results and goodness of fit plots

Table B.4: Full model results: SARE regions

	Knowledge subsystem		Valuation subsystem	
Term	Estimate	SE	Estimate	SE
Regional homophily: Northeast	2.830	0.222	2.450	0.245
Regional homophily: South	1.993	0.181	1.901	0.183
Regional homophily: North Central	2.008	0.147	1.686	0.151
Regional homophily: West	1.041	0.149	1.471	0.124
National homophily: US National	-1.009	0.409	-0.872	0.250
Scale: National (vs. Regional)	0.779	0.122	1.328	0.093
Other subsystem structure	5.230	0.134	0.324	0.434
Anti-centralization	5.078	0.486	3.834	0.413
Triadic closure	0.720	0.052	0.715	0.052
Edges	-6.464	0.146	-5.984	0.150
Survey non-respondent	-1.275	0.135	-1.047	0.113
N respondents per node	0.271	0.025	0.132	0.031
N generic connections	-0.080	0.017	0.029	0.008
Fixed -Inf	-Inf	0.000	-Inf	0.000

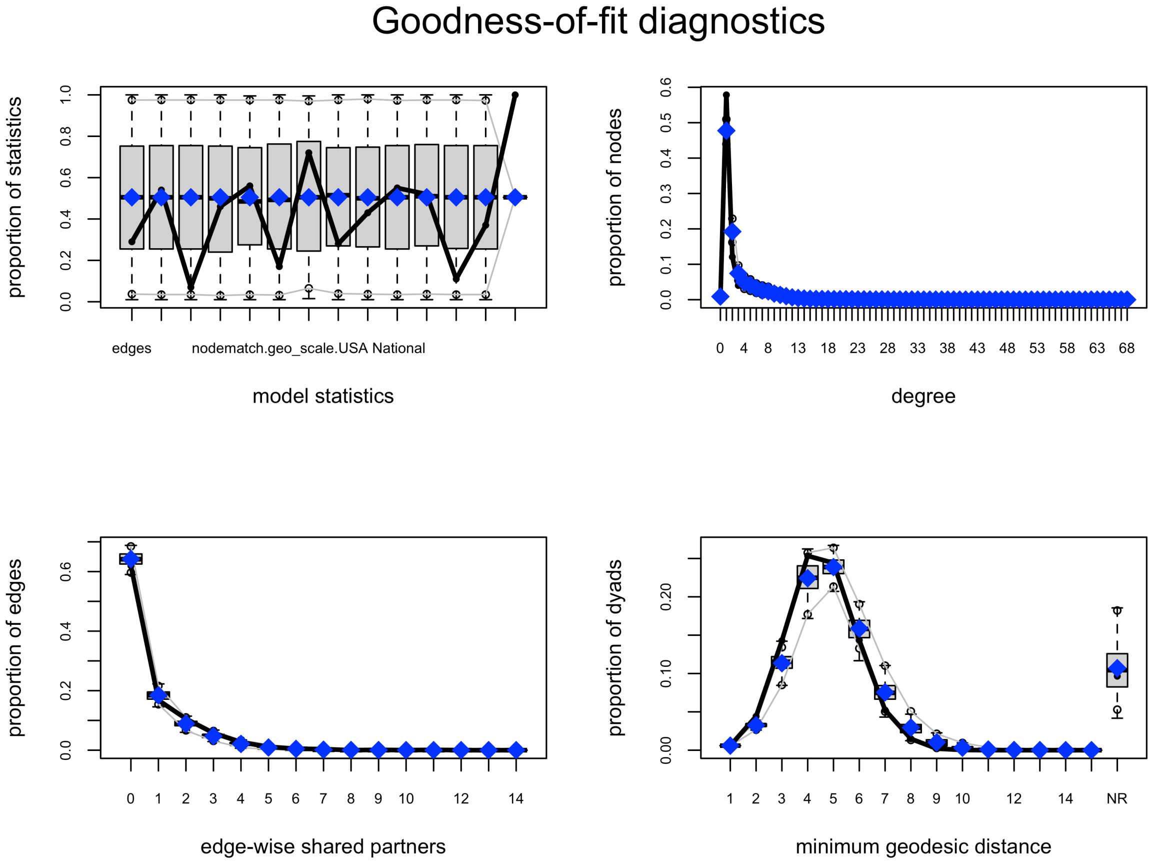

Figure B.2: Knowledge resource subsystem ERGM goodness of fit plots

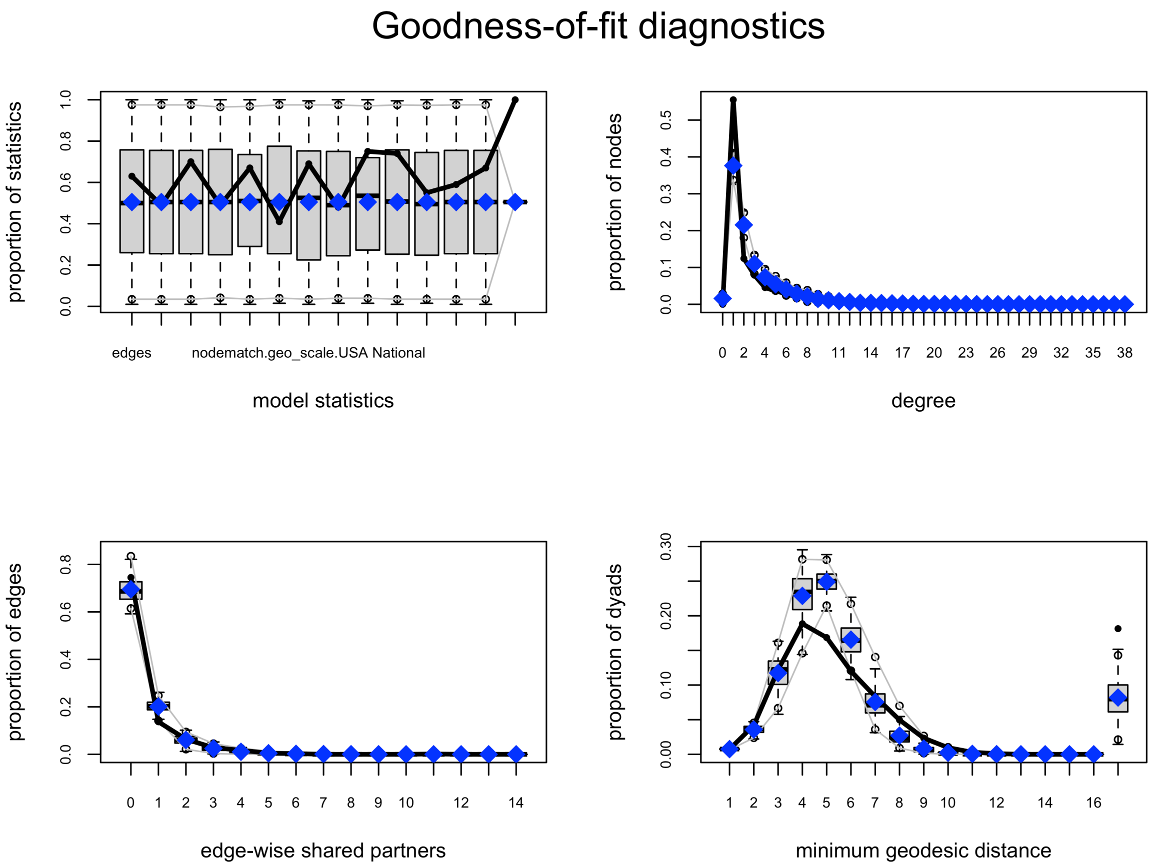

Figure B.3: Valuation resource subsystem ERGM goodness of fit plots

Appendix C

Sample representativeness

Table C.1: Sample representativeness across US regions and spatial scales

	Producer			Company			Researcher			Organization		
Location	n	N	% response	n	N	% response	n	N	% response	n	N	% response
Total	94	416	23	49	130	38	60	117	51	44	93	47
West	53	242	22	13	40	32	13	28	46	10	24	42
North Central	13	74	18	7	17	41	16	34	47	12	18	67
Northeast	9	39	23	7	10	70	8	14	57	3	12	25
South	11	38	29	2	7	29	21	38	55	7	11	64
USA	0	4	0	17	45	38	1	1	100	5	14	36
Canada	6	16	38	2	8	25	1	2	50	6	9	67
Other country	2	2	100	0	0	NA	0	0	NA	0	0	NA
International	0	1	0	1	3	33	0	0	NA	1	5	20

Resource-related topics

Knowledge resource topics: Finding high quality stock seed, Achieving adequate seed yields, Isolation distances, Soil fertility and crop nutrition, Irrigation and water use, Controlling weeds, Controlling insect pests, Controlling disease pressure, Managing climatic effects, Estimating yields (removed for redundancy with Achieving adequate seed yields), Adapting to climate change (removed for redundancy with Managing climatic effects), Managing pollinator habitats (removed because not applicable for many responses), Vernalization for biennial crops (removed because not applicable for many responses), Overwintering for biennial crops (removed because not applicable for many responses), In-field seed production costs (removed because irrelevant to knowledge or valuation resources), Harvest costs (removed because irrelevant to knowledge or valuation resources), Seed cleaning costs (removed because irrelevant to knowledge or valuation resources).

Valuation resource topics: Accessing labor, Accessing land, Accessing capital, Farm business planning, Developing infrastructure, Finding/developing markets, Managing intellectual property rights, Sourcing seed harvest equipment, Sourcing seed cleaning equipment, Requirements of organic certification (removed because irrelevant to knowledge or valuation resources), Contamination from GE crops (removed because irrelevant to knowledge or valuation resources).

ERGM decay parameter selection

We first use all variables of interest to select the `decay` arguments for the `gwdegree` and `gwesp` ERGM terms. We created a function to run through every iteration of values between 0.1-1.0, in increments of 0.1. However, many models did not convergence, forcing us to first evaluate `gwdegree decay` values between 0.1 and 1 with `gwesp decay` value fixed at 0.5. Then based on the best fitting `gwdegree decay` value (0.1), we tested `gwesp decay` values between 0.4-0.9 (the range in which the model would converge) to identify some of the best-fitting values. Models fitting with `gwesp decay` values between 0.7-0.9 had the lowest BIC (Figure C.1). We further explore model fit by comparing goodness of fit statistics across the different values and found the best fitting models when `gwesp decay` is set at 0.9 (knowledge) and 0.7 (valuation) (GOF Figure C.2 and Figure C.3).

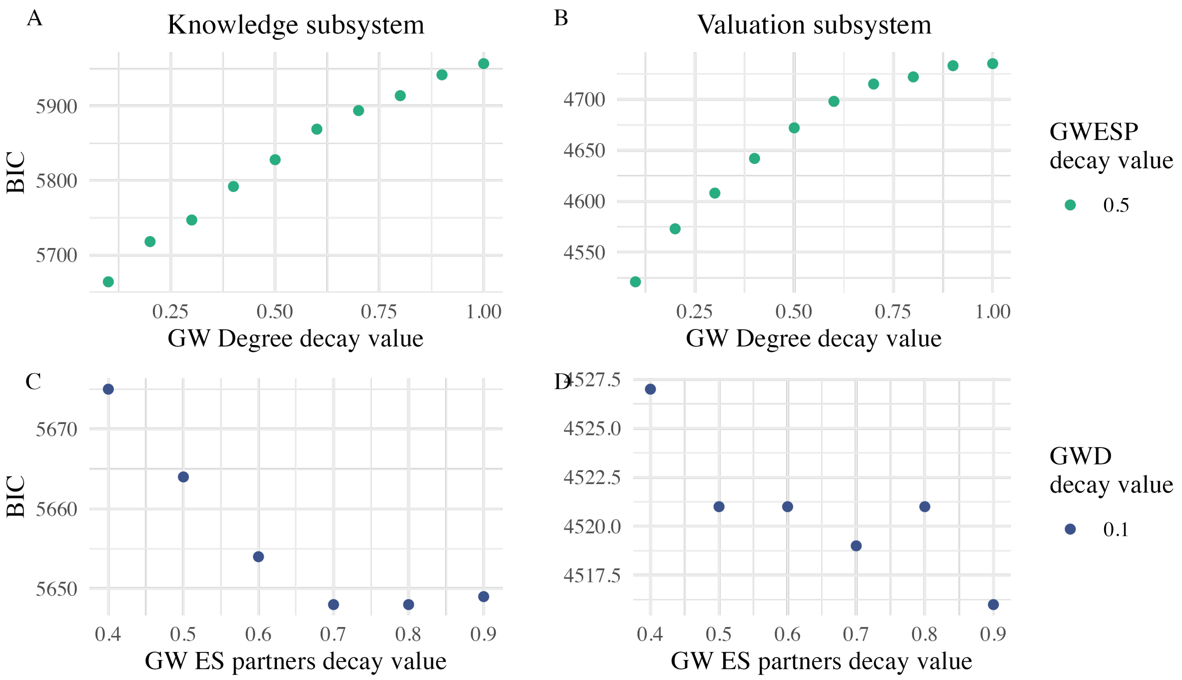

Figure C.1: BIC values across different ERGM geometrically weighted decay value specifications

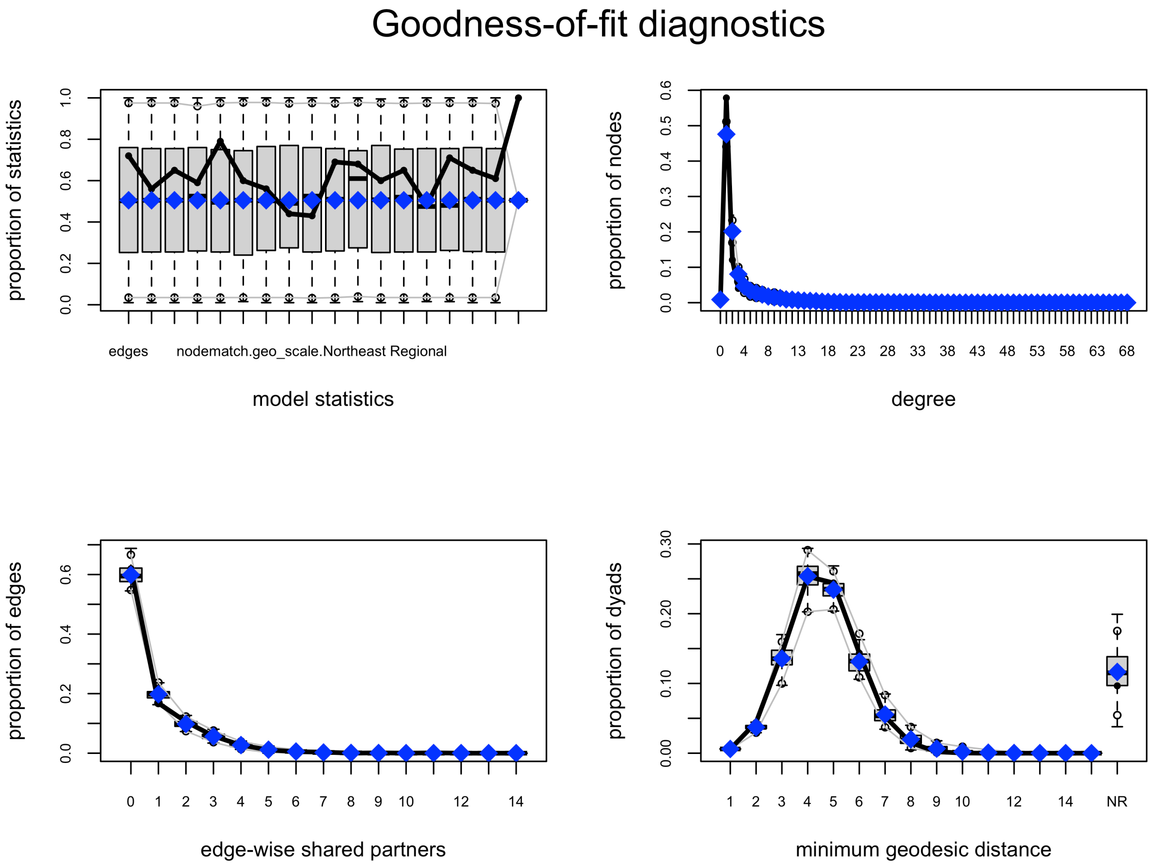

Figure C.2: Knowledge resource subsystem ERGM goodness of fit plots

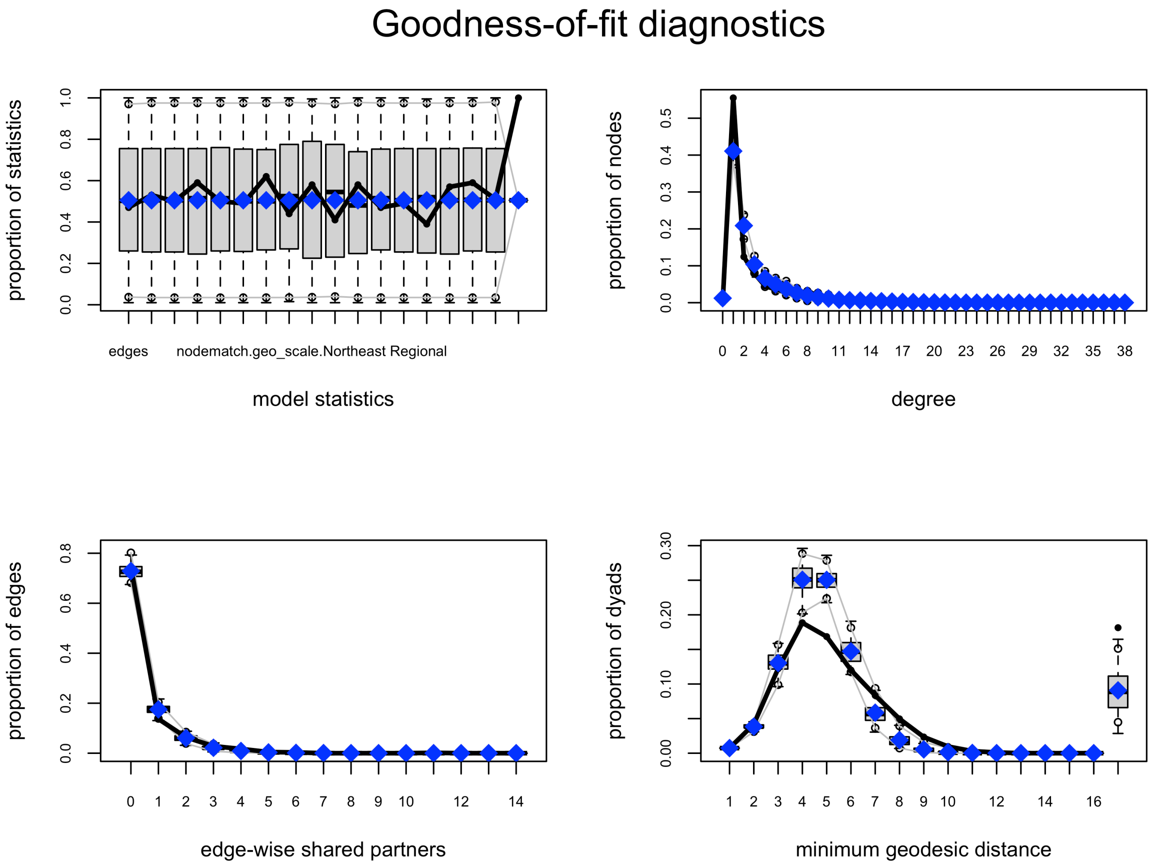

Figure C.3: Valuation resource subsystem ERGM goodness of fit plots

Model building

Once `decay` values were determined, we fit several models building up from the null model with only an edge parameter.

MODEL BUILDING

Table C.2: ERGM comparison for knowledge resource subsystem

Coefficient	Model1	Model2	Model3	Model4	Model5
Anti-centralization		4.73*** (0.45)	4.98*** (0.51)	4.97*** (0.63)	5.24*** (0.51)
Triadic closure		1.4*** (0.08)	0.73*** (0.05)	0.91*** (0.07)	0.73*** (0.05)
Actor-type: Government				0.45** (0.21)	-0.16 (0.29)
Actor-type: University & extension				0.58*** (0.14)	1.12*** (0.15)
Actor-type: Organization				0.52*** (0.13)	0.96*** (0.13)
Actor-type: Company				0.22** (0.11)	-0.1 (0.14)
Regional homophily: Northeast			2.95*** (0.19)	2.3*** (0.37)	2.65*** (0.18)
Regional homophily: South			2*** (0.18)	1.68*** (0.23)	2.02*** (0.14)
Regional homophily: North Central			2.19*** (0.15)	1.95*** (0.16)	1.79*** (0.15)
Regional homophily: West			1.25*** (0.16)	1.55*** (0.17)	1.49*** (0.15)
National homophily: US National			-1.14*** (0.41)	-0.55 (0.49)	-0.91** (0.43)
Scale: National & International (vs. Regional)			0.91*** (0.12)	1.01*** (0.15)	0.93*** (0.12)
Multi-functional tie			5.16*** (0.13)		5.77*** (0.16)
Survey non-respondent		-1.21*** (0.17)	-1.22*** (0.14)	-1.3*** (0.19)	-1.16*** (0.13)
N respondents per node		0.17*** (0.02)	0.3*** (0.04)	0.15** (0.07)	0.14*** (0.04)
N generic connections		-0.01 (0.01)	-0.08*** (0.02)	0.02 (0.01)	-0.02 (0.02)
Edges	-5.11*** (0.04)	-5.73*** (0.16)	-6.76*** (0.18)	-7*** (0.29)	-7.67*** (0.27)
Fixed -Inf		-Inf*** (0)	-Inf*** (0)	-Inf*** (0)	-Inf*** (0)
BIC	9978	8310	5811	7588	5649

Table C.3: ERGM comparison for valuation resource subsystem

Coefficient	Model1	Model2	Model3	Model4	Model5
Anti-centralization		3.53*** (0.4)	3.84*** (0.45)	3.88*** (0.43)	4.38*** (0.49)
Triadic closure		0.93*** (0.05)	0.37*** (0.06)	0.72*** (0.06)	0.43*** (0.07)
Actor-type: Government				0.85*** (0.13)	1.44*** (0.17)
Actor-type: University & extension				0.18 (0.14)	-0.36 (0.19)
Actor-type: Organization				0.1 (0.11)	-0.5*** (0.16)
Actor-type: Company				0.37*** (0.09)	0.52*** (0.12)
Regional homophily: Northeast			2.57*** (0.44)	2.3*** (0.31)	2.38*** (0.39)
Regional homophily: South			1.17*** (0.32)	2*** (0.23)	1.23*** (0.29)
Regional homophily: North Central			0.98*** (0.22)	1.68*** (0.17)	1.11*** (0.24)
Regional homophily: West			1.47*** (0.16)	1.49*** (0.13)	1.38*** (0.18)
National homophily: US National			-0.54 (0.34)	-0.68*** (0.22)	-0.87*** (0.31)
Scale: National & International (vs. Regional)			1.31*** (0.12)	1.15*** (0.1)	1.18*** (0.13)
Multi-functional tie			5.09*** (0.13)		5.39*** (0.15)
Survey non-respondent		-1*** (0.11)	-0.57*** (0.15)	-1.2*** (0.11)	-0.86*** (0.14)
N respondents per node		0.08*** (0.03)	0.07 (0.05)	0.12*** (0.04)	0.15** (0.08)
N generic connections		0.02** (0.01)	0.04*** (0.01)	0.03*** (0.01)	0.02 (0.01)
Edges	-4.9*** (0.04)	-4.89*** (0.11)	-6.64*** (0.2)	-6.33*** (0.21)	-7.08*** (0.29)
Fixed -Inf		-Inf*** (0)	-Inf*** (0)	-Inf*** (0)	-Inf*** (0)
BIC	7606	6656	4640	6374	4519

Full model results

Table C.4: Full model results

	Knowledge subsystem		Valuation subsystem	
Term	Estimate	SE	Estimate	SE
Anti-centralization	5.286	0.501	4.437	0.471
Triadic closure	0.705	0.052	0.412	0.067
Actor-type: Government	-0.256	0.280	1.386	0.160
Actor-type: University & extension	1.202	0.139	-0.305	0.210
Actor-type: Organization	1.056	0.126	-0.558	0.166
Actor-type: Company	-0.030	0.133	0.514	0.116
Regional homophily: Northeast	2.630	0.185	2.438	0.385
Regional homophily: South	1.975	0.174	1.480	0.285
Regional homophily: North Central	1.899	0.152	1.121	0.263
Regional homophily: West	1.514	0.139	1.449	0.183
National homophily: US National	-1.056	0.454	-0.874	0.317
Scale: National & International (vs. Regional)	0.921	0.118	1.190	0.137
Multi-functional tie	5.873	0.187	5.431	0.148
Survey non-respondent	-1.200	0.139	-0.888	0.153
N respondents per node	0.131	0.033	0.151	0.075
N generic connections	-0.007	0.016	0.023	0.014
Edges	-7.814	0.284	-7.074	0.274
Fixed -Inf	-Inf	0.000	-Inf	0.000

Regional subsystem model comparison

We explore the effect of scale on our key structural parameters (anti-centralization and triadic closure) by breaking each innovation subsystem down to four regional scales: West, North Central, Northeast and South. We observe that the key structures remain fairly similar to the national model across all four regions.

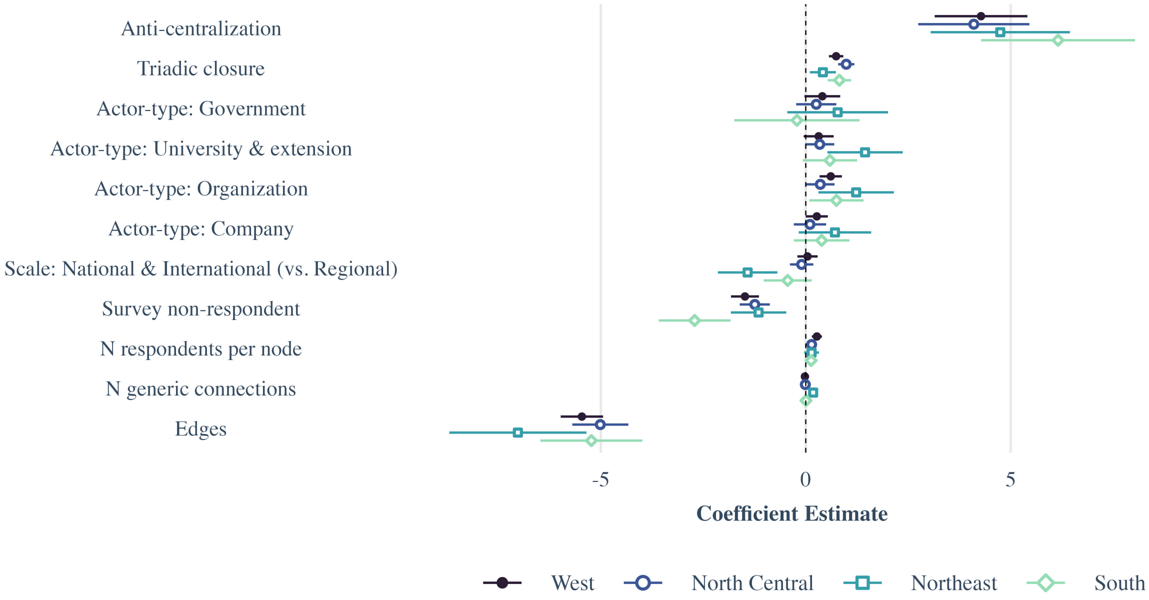

Figure C.4: ERGM coefficient plots of regional knowledge resource subsystem

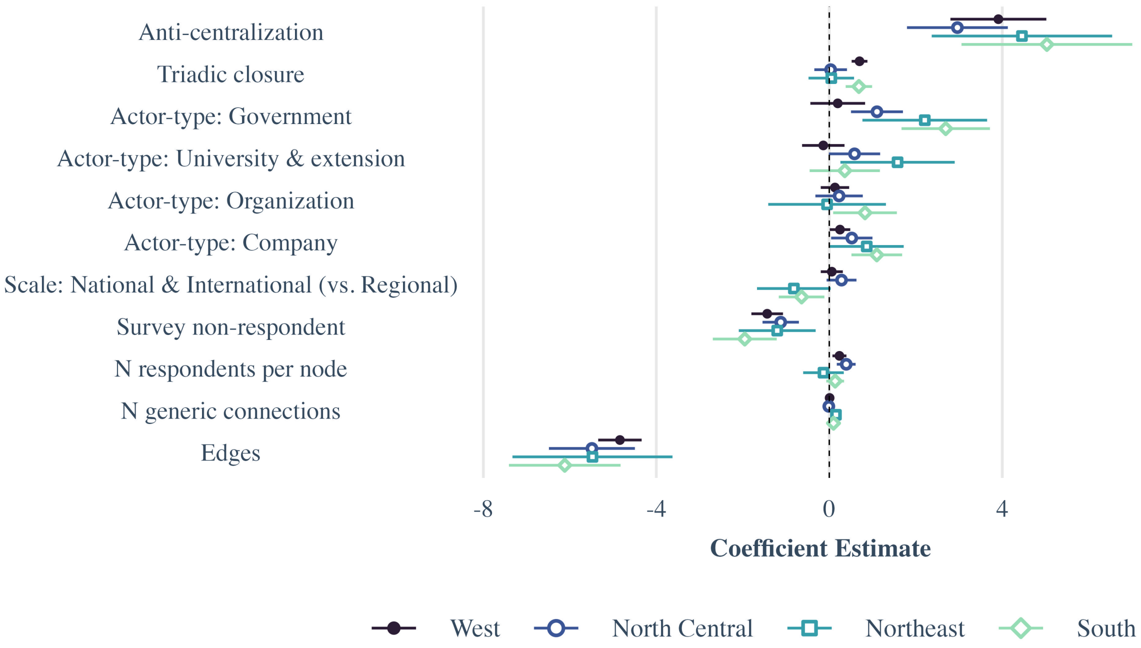

Figure C.5: ERGM coefficient plots of regional valuation resource subsystem

Colophon

This document is set in EB Garamond, Source Code Pro and Lato. The body text is set at 11pt with *lmr*.

It was written in R Markdown and LaTeX, and rendered into PDF using aggiedown and bookdown.

This document was typeset using the XeTeX typesetting system, and the University of California Thesis class. Under the hood, the elements of the document formatting source code have been taken from the Latex, Knitr, and RMarkdown templates for UC Berkeley's graduate thesis, and Dissertate: a LaTeX dissertation template to support the production and typesetting of a PhD dissertation at Harvard, Princeton, and NYU

The source files for this thesis have been compiled at `https://github.com/liza-wood/aggiedown_dissertation`.

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