

Organic Seed Systems

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Organic Seed Systems

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Acknowledgements

“My acknowledgments”

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Abstract

“Overall abstract?”

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Introduction

Short tying it all together

Chapter 1

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

1. Introduction

(Why environmental policy is important, environmental challenges, etc.?)

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 opt-out/exit or find methods for creative compliance if the burden is too high (Bartel and Barclay 2011). Yet, too flexible of policies can also be taken advantage of by free-riders, enabling industries to shirk environmental responsibilities while still

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gaining (Prakash and Potoski 2007). In this paper we ask: **Do flexible environmental standards spare firms from undue burden or enable free-riders?**

To answer this question we study a flexible voluntary environmental policy: the organic certification in the United States and its so-called seed loophole. 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”. 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 fifteen years. We measure organic growers’ use of conventional seed (i.e. their reliance on the loophole) as well as their experiences with seed sourcing barriers, perceptions about organic seed, and their farm operational attributes. 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 more ‘conventionalized’/‘practical’ organic farmers. 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 who don’t see organic seed as important for the success or

CHAPTER 1. ORGANIC SEED POLICY

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 different motivations (Piniero 2020). Though policy design research tends to treat firms as purely rational actors (Timbe and Winter 2015, Prakash and Potoski), farmers especially have different motivations and embrace business models that balance economic and environmental values (Thompson, Brown et al. 2021). These come through as two identities of organic, practical and principled (Darnhofer), 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. (Draft: For organic seed, this means creating a mix of policies that support traditional expansion of organic seed availability and enforcement of the policy, as well as alternative initiatives for principled, grassroots programs)

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 Soderholm 2014). These types of regulatory measures reduce uncertainty in the achievement of environmental outcomes so long as enforcement is in place (Pineiro et al. 2020). However, stringency

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has its drawbacks. The increase of regulation may reduce competitiveness of firms (), counteract voluntary behavior (Barreiro-Hurle et al. 2023), prompt relocation to an area with more lenient policies (), or resistance/creative compliance (Bartel and Barclay 2011).

Flexible environmental policies, on the other hand, use a range of tools to motivate firms via incentives to improve environmental outcomes (Gunningham 1999; Pineiro et al. 2020), and at times permit exceptions/derogations if the regulation is overly burdensome (Romero-Castro et al. 2022). The benefits of flexible policies include reduced tension between firms and government (), as well as room for innovation to ultimately improve environmental outcomes (Loonie et al. 2011; Yuan and Zhang 2020). The drawback of flexible policy tools, however, is that participation can be low, adherence needs to be monitored to avoid free-riding (Prakash and Poroski 2007), and there is less certainty around the environmental benefits (Stuart et al. 2014). Furthermore, vague criteria for exceptions/derogations like the use of 'best available technology' gives wide latitude to firms' discretion (Romero-Castro et al. 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 grant derogations if the costs of complying (as calculated by the firm) are too high (Romero-Castro et al. 2022, Soderholm et al. 2021). In the United States, regulation of manure discharge by animal feeding operations has several exceptions to regulation based on nutrient management plans (Rosov et al. 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, and are then monitored according to the certification standards. These kinds of programs are considered high-cost clubs – stringent voluntary standards that 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 (e.g. NOSB 2004, NOSB 2006) in an otherwise stringent and often challenging certification process (Flaten et al. 2010, Carter et al. 2022).

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 (Endres, Liveseed), where organic growers are allowed to use conventional seed if organic seed is not commercially available. This kind of exception is shared in organic standards around the world, for example the United States' National Organic Program¹, United Kingdom's Soil Association², European Union's Organic Standard, and the East Africa Organic Standard³ all have equivalent exceptions based availability.

¹System resources (also called 'elements') and IS functions generally map onto one another (Binz et al. 2016; Musiolik et al. 2011). Musiolik et al. 2011 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." (p. 1919 2011); And while some elements such as 'value chain coordination' are not in the traditional list of functions, in this paper we generally think of "functions" and "system resources" as interchangeable, but try to primarily use the 'resources' language over the 'functional' language.

²Further, we believe that the structures observed by Musiolik et al. (2020) are limited based on their 'ego-centric' interview methods (Chung et al 2005) which relied largely on the perspective of key actors and the behavior of system builders. 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 partner mode cases.

³We do note, however, that some policy network theory proposes the opposite relationship between

2. BACKGROUND

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.” (NOSB 2008). The intention is that this exception can excuse farmers who experience challenges, particularly as the organic seed market develops (Hubbard 2011, 2016). While there is evidence that the seed system is growing through increased public research spending and the development of new organic varieties (Hubbard et al. 2021; Liveseed?), there is still widespread uncertainty as to how the seed loophole is used by organic growers (Hubbard et al. 2021).

2.2.2 Different models of organic farming

To develop an understanding of how farmers are using the organic seed loophole, we first recognize that farmers (and firms more generally) have different motivations (Bartel and Barclay 2011). Many policy design studies tend to treat firms as purely rational actors (Timbe and Winter 2015). 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’ (p. 287, 2007). But in reality, firm-level decisions are made by actors with varying risk tolerances, entrepreneurial initiatives, and environmental values and strategies (CITES, Ambec). This is especially true for agricultural settings, where securing economic returns exists on balance with other values and operational attributes (Prokopy et al. 2018, Floress et al. 2017).

Farmers make decisions based on a gradient of values ranging from ’farm-as-business’ to 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.

CHAPTER 1. ORGANIC SEED POLICY

'environmental stewardship', though the two are not mutually exclusive (Thompson et al. 2015, dolaglu?). 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 ((Feder and Umali 1993), Dunn et al., 2016), but in other cases it may hinder the willingness to try something new at a large scale, especially if there is no visible economic return (Napier 2000, (Buttel, Jr, and Larson 1990)).

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 & 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 (ibid, Coleman). But when codified into practice as certified organic standards, there was quickly a trend towards 'conventionalization' of organic. 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).

The division between 'principled' and 'practical' organic farmers has created tension around the identity of organic farming (von Shlen 2007, Coleman 2001). 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). 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 (Guthman, Darnhofer), they

3. HYPOTHESES

help us typify different ways that growers may be engaging with the organic standard and its flexibility.

3. Hypotheses

We use the case of the organic agricultural standard to ask: Do flexible environmental standards spare farmers from undue burden or enable free-riders? We propose two sets of hypotheses.

The first proposition tests whether environmental policies add flexibility in order to reduce excessive burden on firms. Organic farming is certainly challenging (Sahm et al. 2012), 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 are using conventional seed.

H1a. Conventional seed use will be highest among growers experiencing more significant organic seed sourcing barriers

H1b. Conventional seed use will decline over time

The second proposition tests whether policy flexibility enables some farmers to take advantage of the policy's leniency (Prakash; Stuart 2014). In the organic seed policy, though guidance for growers and certifiers has tried to define and operationalize the 'commercial availability' exception (NOSB 2018), there is still opportunity for shirking. We propose that those particularly inclined to take advantage of the policy's leniency

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are farmers fitting the 'practical' 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 those 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

4. Methods

4.1 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). 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

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healthy soil, diverse crop rotations, and minimal environmental impact (USDA 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 et al., 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 et al. 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 organic 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, or accredited certifying agencies, 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.

4.2 Data: Organic grower survey

This research combines three cross-sectional surveys of organic seed producers in the United States. These data were collected in 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 maps in Figure 1.1 represent the distribution of our survey respondents. 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 for data analysis for a total of 1,770.

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4.3 Quantitative analysis

4.3.1 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

4. METHODS

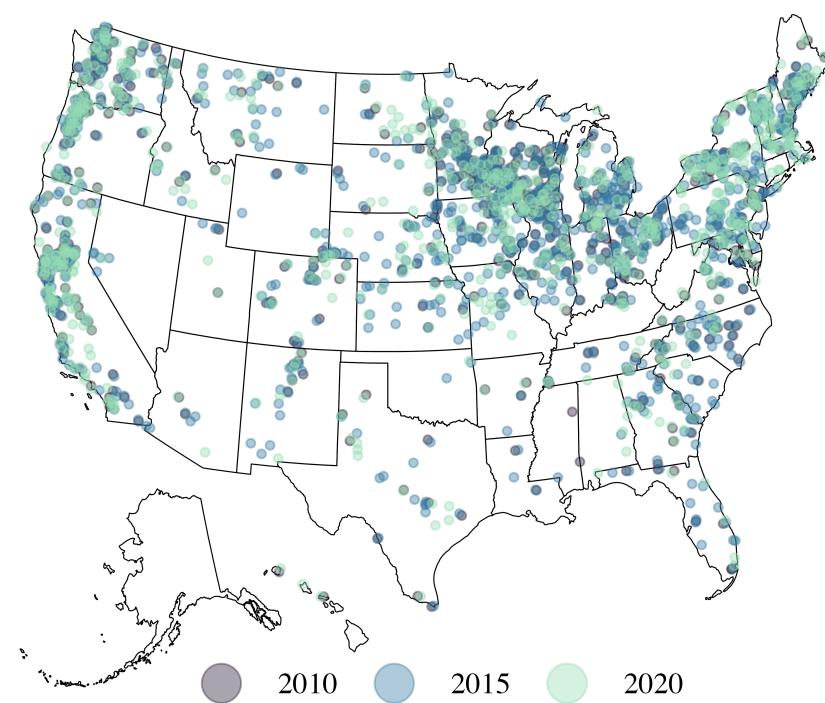


Figure 1.1: Map of the United States depicting survey responses (points) over three time periods, 2010 (purple), 2015 (blue), 2020 (green).

CHAPTER 1. ORGANIC SEED POLICY

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. This includes 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* captures how the organic seed market has changed over time.

The next three variables are relevant to our second hypothesis. Organic growers’ principled *value of organic seed* are derived 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 know 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

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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.

TABLE1.1 need to insert

4.3.2 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 (INLA Documentation: Beta). 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 et al. 2009) available in R Statistical software (R Core Team 2023). INLA uses an Integrated Nested Laplace Approximation – a deterministic Bayesian method for estimating its models. Analysis is available at [\[github.com/liza-wood/organicseed_adoption\]](https://github.com/liza-wood/organicseed_adoption). Variable selection is informed largely by theory rather than model fitting exercises. However, we compare several models and provide measures of model fit in Appendix A-1.

4.4 Descriptive analysis??

5. Results

5.1 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 score an average of 2.6 (between low and moderate factor) in 2010, and that score decreases 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 the integrity of organic has remained consistently high. In the 2010 survey, the average agreement score with the statement that organic seed is important to the success of organic production was 4 (somewhat important), which increased to 4.3 in 2015 and 2020.

5. RESULTS

Table 1.1: Mean values and standard deviations (reported in parentheses) for the key variables from the organic grower survey for each time period

Questions	stats2011	stats2016	stats2021
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 (545)	799 (799)	408 (408)

The operational profile of organic growers matches the profile of agricultural production more generally in that farm sizes are increasing ((Summer 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 the 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.

5.2 Policy flexibility for 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-2.

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 requirements have effect sizes of 0.14, 0.13, and 0.11, 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 0.14 (14%). 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 -0.17, suggesting that compared to the baseline data in 2010, growers are planting 17% less of their acreage to conventional seed. Likewise in 2015, growers are planting 33% less of their acreage to conventional seed.

{width=“6.5in” height=“3.25in”} These results support our first hypotheses: H1a) Conventional seed use will be highest among growers experiencing more significant organic

5. RESULTS

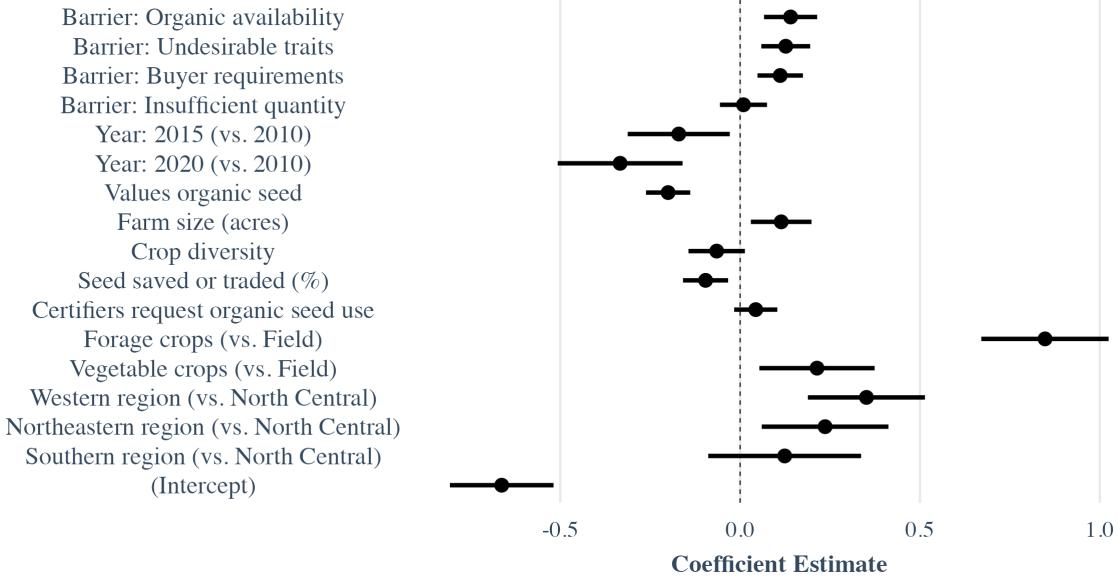


Figure 1.2: Coefficient estimates and credible intervals for the beta regression assessing the proportion of total acreage of a growers main crop planted with conventional seed.

seed sourcing barriers and H1b) Conventional seed use will decline over time. 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.

5.3 'Practical' farmer profiles rely more on policy flexibility

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

CHAPTER 1. ORGANIC SEED POLICY

integrity of organic farming has a considerable effect on how much of acreage is planted 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 11% 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.

These results support all three of our second hypotheses: H2a) Conventional seed use will be highest among those with who place low value on organic seeds' contribution to organic integrity, H2b) Conventional seed use will be highest on large farms, and H2c) Conventional seed use will be highest on low-diversity farms. 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 85% more of their acreage to conventional seed compared to field crop growers, while vegetables crop growers plant an estimated 21% 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 0.35 and 0.24, 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),

6. DISCUSSION AND CONCLUSION

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 20-39% more acreage to conventional seed than principled farmers in 2010, 22-73% in 2015, and 8-20% in 2020. The standard errors around these estimates are plotted, but are so small that they cannot be seen in the figure. We run these same predictions for Field and Forage crops (available in Appendix A-3) and observe even higher differences between the two farm profiles over the three time periods.

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5.4 Descriptive??

6. Discussion and conclusion

6.1 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

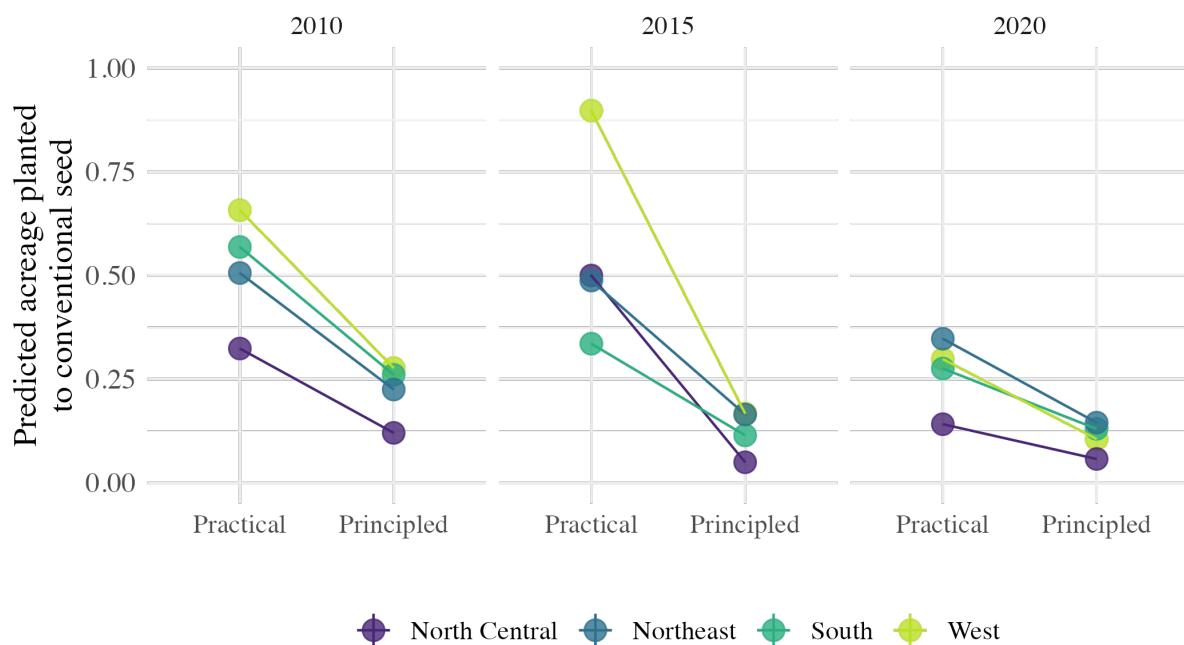


Figure 1.3: Predicted mean estimates and their credible intervals (not visible due to small size) for vegetable crop growers of two farmer profiles. Estimates are made for each region of the US, represented by the different colored points (see legend). The points represent the mean estimates and lines connecting points highlight the difference between practical and principled growers in each time period.

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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).

What do I actually contribute? (struggling here)

- These results move beyond a singular assessment: flexible > market-based policies are good because they support innovation > (Ramanathan) or flexible voluntary standards are bad (Angus 2015). > It generates a more nuanced discussion around how to tweak policy > to account for the different motivations of growers.
- 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 > different motivations (Pinero 2020). Though policy design > research tends to treat firms as purely rational actors (Timbe and > Winter 2015, Prakash and Potoski), farmers especially have > different motivations and embrace business models that balance > economic and environmental values (Thompson, Brown et al. 2021). > We make the point that firms, farmers, and people generally > respond to environmental policy stringency (and flexibility) > differently, and so tools need to be designed to account for this > (Pinero et al. 2020)..

This is also an innovation system/innovation policy problem

- By identifying that there are barriers to sourcing, this calls upon > innovation policy for organic seed. Namely, to get the balance > right, the organic seed

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standard may require complementary > policies that support innovation to build a stronger organic seed > innovation system more generally (Rogge and Rechiart). In short, > we need a wider mix of policies if we really want to improve > organic seed sourcing.

- Basically we need to look beyond single policies and think more > broadly about the mix that they're in
- Though the standard supports organic seed market development and > innovation by requiring its use, it simultaneously creates > challenges for incentivizing entrepreneurial activity due to this > exception, and leaves the decision to certifiers for assessing > commercial availability and viable alternatives ([Renaud et al., > 2016](#)).

6.2 Reckoning with identities of environmental movements

While finding the right policy tool is central to improving environmental outcomes (Gunn), it bypasses broader discussion about the identities that motivate firms, farmers, and people generally to participate in 'sustainability transitions' (). Our results highlight a tension in the organic movement, between practical and principled farmers, that exists across efforts for social and environmental change more generally (Smith 2012).

On one hand, participants in grassroots, alternative sustainability movements often do not want to replicate the systems they developed as an alternative to (Smith and Raven; Pasucci). For example, farms like Bee Heaven Farm in Florida produce mixed vegetables for direct sales on five acres, and grow out seed for use on their operation. Though organic, farms like these are re-asserting their ethic through initiatives like the "Real Organic" label, that oppose what is perceived as the industrial co-opting of the organic standard

6. DISCUSSION AND CONCLUSION

([\[www.realorganicproject.org\]](http://www.realorganicproject.org)). This is true for some parts of the organic movement (Youngberg) but also movements like the open source software initiative (Jain et al. 2023), open-source seed initiatives (Montenegro de Wit), community energy initiatives (Smith 2013), and Hackerlabs (Smith).

On the other hand, participants in more traditional sustainability initiatives want to scale to replace the mainstream modes of production in order to have the widest impact (Smith and Raven). 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 merger with conventional operations and 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 same model is aspired to for several alternative energy technologies like wind \(\) and fuel cells \(\).](https://calorganicfarms.com/our-story/)

By and large, environmental sustainability initiatives are designed and evaluated based on the metrics of the latter, traditional approach. As a result, the focus is largely on getting incentive structures right so that pro-environmental behavior and innovation can flourish and scale (Prakash and Potoski). Yet, our results point to the coexistence of both alternative and traditional visions of sustainability transitions through the clear difference in seed sourcing behavior by principled and practical farmer profiles. Based on these findings, we propose that designing a well-balanced environmental policy needs to reckon with these multiple, sometimes competing identities. This reckoning includes recognition of how different policies cater to different identities and visions within sustainability transitions.

6.3 Organic policy recommendations

In this section we propose recommendations related to the United States organic standard, recognizing the multiple identities within organic farming. Recommendations relate to the organic seed policy itself, as well as innovation policy more broadly that shapes the way organic seed is developed and made available.

Make more seed available

- Support innovation via:
 - > Continue funding for research and organic > variety development and support seed producer education and > expansion
 - Not just through traditional pipelines like plant patenting, but > also grassroots initiatives like commons-based > breeding/open-source seed initiative

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- Direct resources towards a diverse portfolio of > ‘pre-competitive’ agricultural programs to support diversity > – climate change adaptation, minor crop work, etc
- Continue funding public seed collections

Strengthen the organic seed requirement

- Require organic growers to demonstrate improvement in organic seed > sourcing
 - This was recommended by NOSB in 2018 – has it been taken on? > Not by the time of the SOS 2022 report.
 - For example, growers over a certain income threshold should > contract/take on research

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- Improve availability resources
 - Measuring availability has been addressed in the EU through the > creation of an organic seed database, in which all organic > seeds must be registered > ([LiveSeed]). > And consequently, these derogations are slated to be phased > out by 2036. The US has tried this but failed...
- Increase certifiers enforcement ability
 - First, focus on substantive non-compliance notices, rather than > administrative (Carter et al. 2022)
 - Consider who exceptions are for: biggest farmers? Or most > diverse?
- Ultimately, goal is to consider tightening or closing the seed > loophole

The goal should be not to preference practical or principled, completely. In order to give principled a chance of staying in it, there should also be policies that challenge the highly consolidated nature of seed in the US. Enforcing anti-trust and protecting access to plant genetic material

In this way mixes are not just about utilizing a wide range of tools, but also supporting a diversity of pathways towards compliance, without preferencing a select farmer profile.

Chapter 2

Mapping the spatial boundaries of the United State's organic seed niche: An empirical test of the Global Innovation System framework

1. Introduction

Innovation systems (IS) are a complex network of actors and institutions that interact in support of developing and diffusing new technological and/or social innovation ([Bergek 2008](#)) ([Bergek et al. 2008](#)). The field of IS has broadly led to insights that support policy recommendations for fostering innovation for sustainable development, particularly from 'niche' phases.

1. INTRODUCTION

Yet, studies on innovation have long been grappling with the challenge of defining meaningful spatial 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 in developing a more generalizable understanding of how and why systems evolve (Binz, Truffer, and Coenen 2014). This generalized information about the evolution of IS has been critiqued for lacking in the IS literature (Kern 2015; Markard, Hekkert, and Jacobsson 2015).

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), which generates theory regarding predictors of IS spatial scales and sets out an approach for operationalizing those predictors. The theory 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. Recent scholarship expands the scope of the GIS framework by highlighting the importance of vertical structural couplings, which link actors at different geographies and scales (MacKinnon, Afewerki, and Karlsen 2022; Rohe 2020), and horizontal structural couplings, which link the resource subsystems (Tsouri, Hanson, and Normann 2021). 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, which is an example of 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

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valuation, theoretically positioning it as a 'spatially sticky' regional innovation system. Spatially sticky systems are those where knowledge and market related resources are territorially embedded, making for closely knit regional networks (Binz and Truffer 2017). And indeed, actors within the system see organic seed as an IS that is decentralized and regionally based in order to foster a diverse and redundant social and ecological system (Rohe et al. 2022; Wood 2022).

We focus on three main hypotheses to test the GIS in the context of the organic seed innovation system. First, we expect that as a spatially sticky IS, the structure of the organic seed network will reflect strong regional embeddedness in the structure of both its knowledge and valuation resource subsystems (Binz and Truffer 2017). Second, we expect that actors at higher operational scales will play a coordinating role in linking these regional networks, reflecting vertical coupling (Bergek et al. 2015; F. Vantaggiato et al. 2023). Third, we expect that there will be complementarities between the two subsystems, whereby activity in one will positively affect activity in the other, reflecting horizontal coupling (Tsouri, Hanson, and Normann 2021). We test these hypotheses using network data collected from surveys of organic seed innovation system actors and analyze them using social network analyses.

We find support for all three hypotheses. First, the spatial structures of the organic seed system's resource subsystems align with the GIS expectations based on the innovation mode and product valuation dimensions. Second, our findings suggest that higher-scale actors encourage vertical structural coupling by acting as coordinating bridges between lower-scale actors. And third, the knowledge and market based subsystems are horizontally coupled in that actors' activity translates across both subsystems, linking resources across the whole innovation system network. These results suggest that though regions are the most relevant spatial boundary for this type of innovation system, national and

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international-scale actors still serve a prominent role in providing resources to territorially embedded 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.

Altogether, this paper makes both theoretical and methodological contributions. Theoretically, we test the developing GIS framework related to innovation system boundary-setting and the role of actors' geography and scales in building resources (Binz and Truffer 2017; Rohe 2020; Tsouri, Hanson, and Normann 2021). Particularly, 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. This contribution is part of a broader effort to add theoretical depth to innovation systems scholarship in order to outline generalizable understanding of system boundaries (Kern 2015; Markard, Hekkert, and Jacobsson 2015). Methodologically, we employ structurally explicitly network analytical approaches, Exponential Random Graph Models, which have rarely been applied in empirical work on innovation systems (Hermans et al. 2017). This is a response to calls for expanding methodological tools in innovation system studies (Binz and Truffer 2017; Binz, Truffer, and Coenen 2014) and sustainability transitions more generally (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.

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 sub-fields, including national, regional, technological and sectoral innovation systems (Carls-son 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 place 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 place (Rohe 2020; Rohe and Chlebna 2021). Beyond regional heterogeneity, actors operate at different scales (e.g. local producers, regional organizations, national government actors, multinational companies). The scale

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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 (F. 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 place 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 knowl-

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edge, investment/capital, market, and legitimization 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 (van Alphen et al. 2010; Hermans 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 place 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

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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 & Truffer, 2017, p.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 legitimization 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 places 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 subsystem 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 dimen-

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sions 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, 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, knowledge is created through practice and customized 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 places and contexts. The IS resource relevant to this dimension is the knowledge resource, whereby 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 & Truffer, 2017, p.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,

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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 in the ST mode 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') (Fig 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 (Fig 1. Quadrant III). The other two types mix these dimensions, whereby 'market-anchored' systems have spatially footloose knowledge-related subsystems but sticky valuation-related subsystems, while 'production-anchored' spatial scales are reversed across subsystems.

{width="4.566288276465442in" height="3.834511154855643in"} Of course, these are stylized types that omit other complex dimensions (Binz and Truffer 2017). 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

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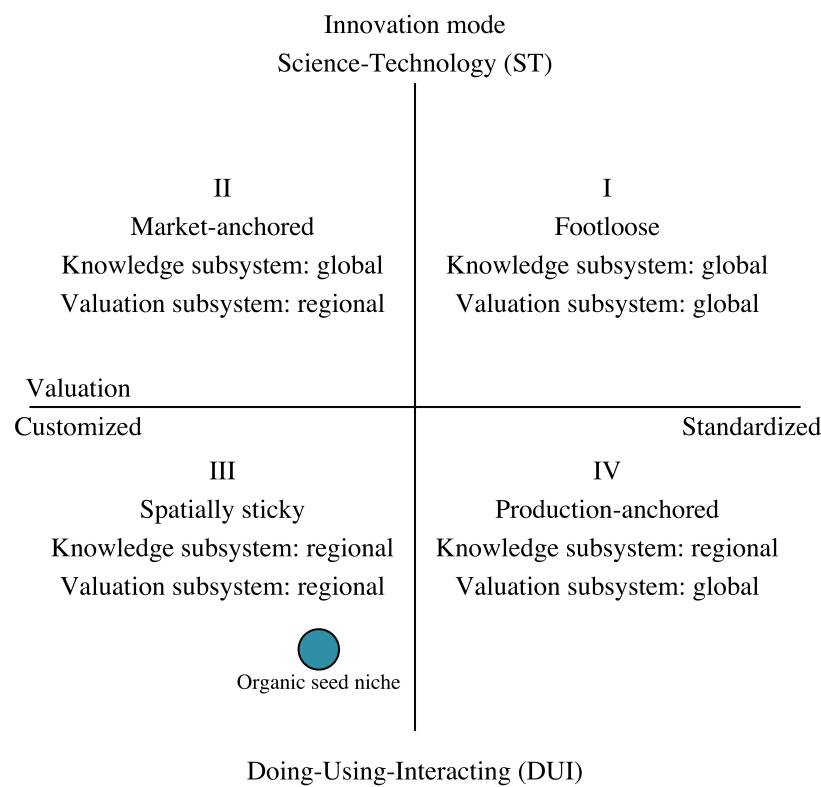


Figure 2.1: Global Innovation System typology, modified from Binz and Truffer 2017

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DUI modes (Jensen et al. 2007; Tsouri, Hanson, and Normann 2021), and placement on the typology may change over time (Binz and Truffer 2017). However, this framework sets out a baseline for theory building across several complex dimensions, which is a contribution for developing a more generalizable understanding of how and why systems evolve.

2.4 Organic seed innovation system

To test the GIS theory predicting the spatial boundaries of an innovation system, 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 play 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 (Rohe et al. 2022). Historically

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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 stakeholders (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; Wood 2022).

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 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). 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.

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2.4.1 Hypotheses for a regionally sticky innovation system

We propose that the organic seed niche is positioned 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 communities and within-region homophily

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

Beyond coupling within-regions, we also evaluate the importance of vertical and horizontal structural coupling. While the GIS 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 actors as coordinators/bridges (Bergek et al. 2015; F. Vantaggiato et al. 2023). Specifically, we hypothesize:

H2: National and international-scale actors will serve as bridges between regional-scale actors, operationalized by national-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 Norrmann 2021) by hypothesizing:

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

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 stakeholders related to the organic seed innovation system. 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

3. METHODS

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, 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),

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and organizations – between 2020-2022. The surveys asked respondents to describe their operation and/or position, the challenges they face in their role, the crops they work with and breeding priorities, and their perceptions on climate change and intellectual property rights. The survey also asked respondents 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](#)). 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 across the different roles for 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 nodes according to the USDA's Sustainable Agriculture Research and Education regions: West, North Central, South, and Northeast. We explore the implications of this regional boundary choice in Supplemental Material B-1. Actors from these regions are represented as follows: 89 actors operating at the Western regional scale, 48 at the North Central regional scale,

3. METHODS

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

Region...scale	Population..N.	Sample..n.	Response.rate....	Network.actors..n.
West Regional	334	89	27	194
North Central Regional	143	48	34	120
South Regional	94	41	44	87
Northeast Regional	75	27	36	59
Pacific Regional	17	6	35	13
Central Regional	8	3	38	7
Prairie Regional	2	1	50	3
Atlantic Regional	1	1	100	7
Other country Regional	2	2	100	14
USA National	64	23	36	88
Canada National	7	4	57	15
Other country National	0	0	NaN	11
International	9	2	22	27
Total	756	247	33	645

41 at the Southern regional scale, and 27 at the Northeastern regional scale. There are also 13 respondents that operate at regional levels across Canada, 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. Detail on these scale designations is available in Supplemental Material B-2. 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.

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

Functional.subsystems	Resource.subsystems	Types.of.relationships
Knowledge	Knowledge creation	Information acquisition and exchange, Research partners
Valuation	Resource mobilization	Seed acquisition, seed exchange, research funding
Valuation	Market formation	Licensing agreements, contracts, rent, buy, and/or sell

3.2 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 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 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 legitimization function. Of the 247 survey respondents, 188 answered network questions, and these respondents identified 497 other entities through 2395 connections. Because 20%

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(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 actor attribute). As a result, the final innovation system network includes a total of 1908 ties between 645 uniquely identifiable nodes across the different spatial scales (Table 2.1). 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 test whether the two resource-based subsystems in the organic seed network are coupled within the regional scale (i.e. ‘local’), within the higher scales (i.e. ‘global’), and/or between regional and higher scales. These analyses are a structurally descriptive n-clan approach and a structurally explicit Exponential Random Graph Modeling (ERGM) approach.

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

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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. 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 (T. A. Scott and Ulibarri 2019). These n-clan categorizations can suggest a trend in spatial structure, but this method is limited in the ability to statistically test within or between scale preference and prevalence.

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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 (T. A. 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 then estimates the likelihood that these 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 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 geographic attribute. 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 regional scale. The endogenous parameter in our model is a matrix representing the structure of the subsystem not being tested (e.g. when evaluating the knowledge

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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 endogenous structural terms as control variables. The first three, edges, degree, and triangulation, 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 triangulation (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 survey data collection 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 (T. 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, relying primarily on the 'statnet' package (Handcock et al. 2019) for analysis and the 'ggraph' package (Pedersen 2022 CITE) for visualization. Code is

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available [LINK FORTHCOMING] and data is available upon request.

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. 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 are from Canada, though there are also 17 actors from both scales represented as “Other country” from various global contexts (Europe: 8, Africa: 3, Middle East: 2, Latin America: 2, Asia: 2).

4.2 ERGM

Next we present results from our two Exponential Random Graph Models, which express 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. When interpreting log-odds in the figure, a basic intuition is that values less than

Table 2.3: Actors' geographic representation of innovation subsystems by count and percent

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

zero represent lower probabilities of forming a tie and values greater than zero represent higher probabilities of forming a tie. To discuss specific statistics throughout the text, we transform the log-odds coefficients into odds.

4.2.1 Organic seed as a spatially sticky regional 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 model represent the estimated likelihood of an actor from a certain region or scale (i.e. four regions in the US or operation at 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.

4. RESULTS

Across both innovation systems, actors from each region – Northeast, South, North Central, 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 16.5, 8.2, 9.2, and 3.3 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 14, 3.9, 2.8, and 4.3 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 support H1a and H1b, as there is strong within-region affinity within both subsystems, representing regional stickiness of our 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).

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4.2.2 Vertical coupling via national-scale bridges

Network statistics about the affinity 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 model results signaling 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

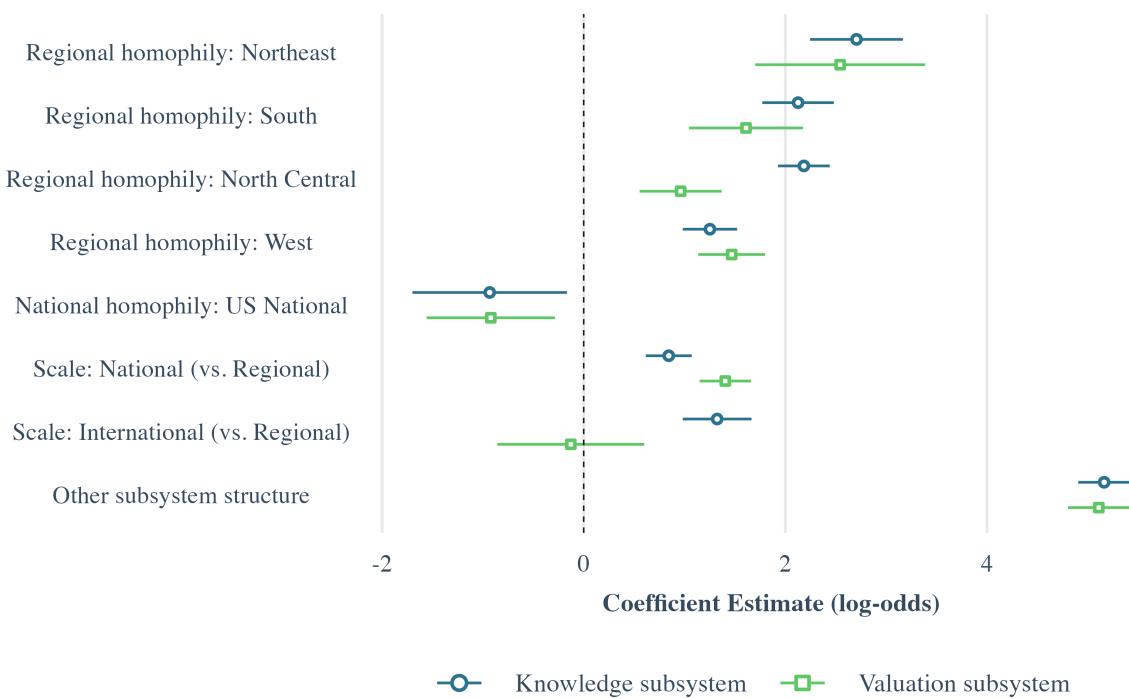


Figure 2.2: Coefficient plot for ERGMs of the knowledge and valuation subsystems. Shapes represent the coefficient estimate, reported as log-odds, and bars represent confidence intervals.

4. RESULTS

regional-scale actors.

This role of higher-scale actors as bridges is further supported by the significant and positive estimates for tie formation at the national and international scales. Where homophily represents the probability of a connection to those with a shared attribute, 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 2.3 to 1 in the knowledge subsystem and 4.2 to 1 in the valuation subsystem. For international actors, these odds are 3.8 to 1 and .9 to 1, respectively, though the valuation subsystem estimate is not significant. These estimates indicate that ties to higher-scale national and international actors are more likely than ties to regional-level actors. These results support H2, suggesting vertical coupling via higher-scale actors who are strongly linked to regional actors but not to one another.

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 organic seed 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 166 and 167 to 1 for the knowledge and valuation subsystems, respectively.

5. Discussion and 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. This research contributes to the theoretical underpinnings of the GIS, as well as adds to the methodological toolkit for analyzing innovation systems using structurally explicit network analysis.

5.1 Developing GIS theory

Results from our analysis of the organic seed system align with the expectations of the GIS in that 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 in order to outline generalizable understanding of system boundaries (Markard, Hekkert, and Jacobsson 2015).

This paper is among the handful of studies that have begun to test the GIS 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 (e.g. wind

5. DISCUSSION AND CONCLUSION

power), which tend to represent a mix of sticky and footloose spatial structure that rely, to some extent, on strong global networks (*ibid*). And sustainability transitions more generally 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 valuation subsystem, 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 setting effective policies.

Beyond validating the theory outlined by the GIS, 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 network governance studies (F. Vantaggiato et al. 2023).

Relevant to the vertical coupling results, we want to emphasize a distinction between two types of vertical coupling. 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

CHAPTER 2. SPATIAL BOUNDARIES

lower and higher scales, which we operationalize as mixed-scale clans and infer from the national scale actors' simultaneous heterophilic tendency (i.e. preference to create ties with non-national actors) and strong probability of tie formation compared to regional actors. While we only observed the latter in our case, we propose 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 forms that structure can take (e.g. supporting coordination or cooperation (Berardo and Scholz 2010)).

Regarding horizontal coupling, the effect of one resource-based subsystem on another, we find evidence for strong between-subsystem spillover effects. 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 (F. P. 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 IS 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 (e.g. Hermans et al., 2013; Musiolik et al., 2012; van Alphen et al., 2010), we employ an Exponential Random Graph Modeling approach which is seldom applied to 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 compositional methods (e.g. Giurca & Metz, 2018; Rohe & Chlebna, 2022) and structurally explicit methods (T. A. Scott and Ulibarri 2019).

5. DISCUSSION AND CONCLUSION

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), test theory, 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

- We used the US seed population as a starting point, but 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 (helps us understand the spatial reach > of the US-based seed system)
- 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.

5.4 Policy recommendations

need to draft

Chapter 3

Innovation system network formation: Resource constellations shape cooperation in the organic seed niche

1. Introduction

How to build a successful innovation system has long been a topic in the sustainability transitions literature. Much attention has been paid to the functions that support innovation systems, such as knowledge creation, legitimacy building, capital support, and market formation, which are the processes fueling the development and diffusion of an innovation. Complementary to these functions are structural features, which define the architecture that helps these functions develop, accrue, and/or dissolve.

While it is broadly agreed that there is no single recipe for how innovation systems are

1. INTRODUCTION

built (Bergek et al. 2008), recent attention has been paid to innovation systems' structural features and the conditions that predict them (Binz and Truffer 2017; Binz et al. 2014; Hermans 2013). Particularly, the resource-based theory for network building has recently been proposed (Musiolik et al. 2020), but empirically testing this theory is still in early phases (Cholez and Marie-Benois 2023). Furthermore, though actor agency is central to innovation system building, there is room to better define the different actors in the system and the roles in system building.

To address these gaps, this paper asks: **What are the conditions driving innovation system formation? And what actors are most involved in the formation of innovation networks?** We connect recent resource-based theories for network building to policy and social network literature in order to develop a testable hypothesis about the relationship between system resources and network structure. Specifically, we propose that closed triangle structures ('partner modes') will be more prevalent than open triangles ('intermediary modes') in innovation system networks that have existing, decentralized resources. We then draw on the multi-actor perspective to hypothesize why some actors may be more or less active across subsystems in the network. Specifically, we propose that non-profit stakeholders will be more active in the knowledge resource subsystem, and for-profit stakeholders will be more active in valuation resource subsystems.

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 800 actors using survey data collected between 2020-2022, and operationalize two resource subsystems – knowledge and valuation subsystems – based on the relationships that actors define. Based on these data, we use a structurally explicit network analytical approach, exponential random graph modeling, to statistically determine whether certain social processes and actor compositions are more or less prevalent in the organic seed niche's functional

subsystems.

We find support for the resource-based hypothesis that predicts structure based on resource availability. Both the knowledge and valuation resource subsystems have existing but decentralized resources, and these networks rely significantly more on 'partner modes' of system building (closed triangles) than intermediary modes (open triangles). We also find support for our hypotheses about actor composition, where actors' institutional logics align with their relative activity in the different resource subsystems.

DRAFT Concluding remarks: We agree with Musiolik et al. (2012) in arguing 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" (p. 1034). ; Outlining the building blocks of innovation systems helps policymakers better understand the circumstances under which certain system building strategies should be put into place.

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 et al. 2012) have been influential in delineating the processes that foster an innovation system's formation. For example, functions like knowledge development and diffusion, legitimization of the technology, resource mobilization, and market formation provide key resources necessary to support an innovation's

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success (Binz et al., 2016). The original functional perspective argues 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 et al. 2012), which has in turn minimized attention placed on the structural building blocks of innovation systems.

There has been renewed attention on the structure of innovation system formation (Musiolik et al. 2020; Binz and Truffer 2017). One key example is how actors can employ different modes of 'strategic system building' (Musiolik 2020; Cholez and X 2023). System building is the creation and strengthening of innovation system-wide resources, including functions¹ like shared knowledge, legitimization, market formation, and value-chain creation (Musiolik et al. 2011; Musiolik et al. 2012, Hellsmark and Jacobbson 2009). Recent research has focused on how these system resources are intentionally developed by building relationships, specifically within formal networks (Musiolik and Markard 2011). These kinds of inter-firm efforts are important for collective gains of an innovation system (Van de Ven 2005).

Systems building theory lays out two types of multi-actor structures within innovation system networks that can support system resources. The first is 'partner mode,' whereby actors in the network share complementary skills and assets to co-create resources that support system-level functioning. The second is 'intermediary mode', whereby actors work together via an intermediary actor that can generate resources that support both

¹System resources (also called 'elements') and IS functions generally map onto one another (Binz et al. 2016; Musiolik et al. 2011). Musiolik et al. 2011 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." (p. 1919 2011); And while some elements such as 'value chain coordination' are not in the traditional list of functions, in this paper we generally think of "functions" and "system resources" as interchangeable, but try to primarily use the 'resources' language over the 'functional' language.

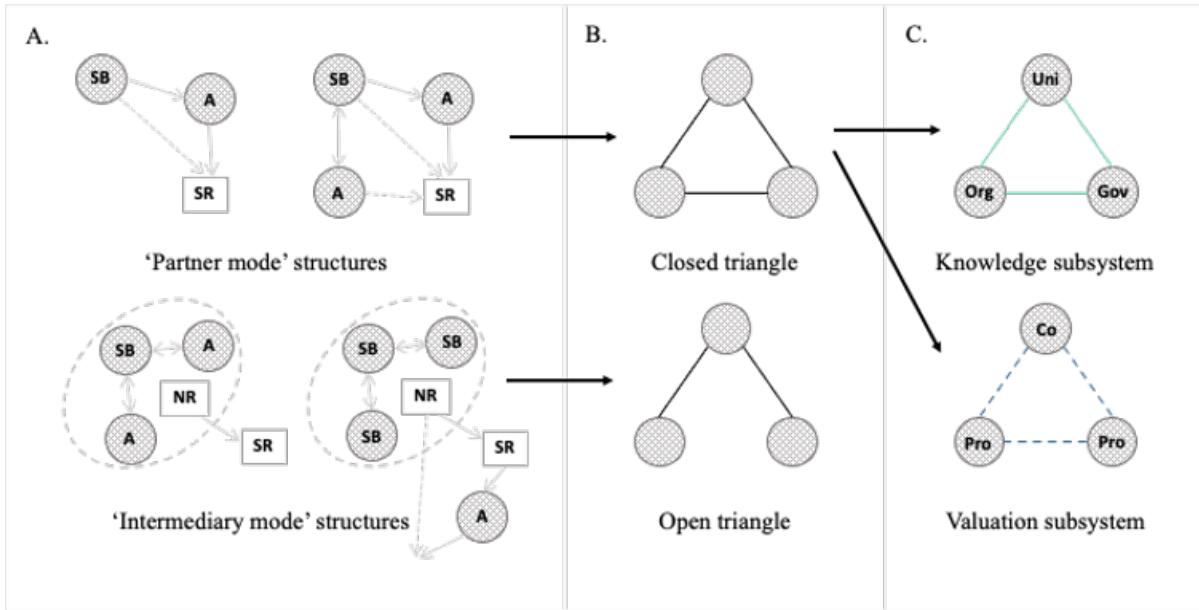


Figure 3.1: A) Multi-actor network structures, adapted from Musiolik et al. (2020). Partner mode structures (top) and intermediate mode structures (bottom) show how system builders connect to other actors to build system resources (SR) and network resources (NR). Circles represent different actors, labeled as system builders (SB) or complementary actors (A). 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).

the network, such as trust and reputation, as well as systems-level functioning (Muisolik et al. 2020). The two structures are displayed in Figure 3.1A. The key structural difference is that the intermediary mode structure requires the creation of network resources such as trust and reputation, and so 'a system builder coordinates activities in a network of collaborators to develop new, intermediate organizational structures' (p.10, Musiolik et al. 2020). We use these structures as a starting point for linking the innovation systems and social networks literatures.

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2. BACKGROUND

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 (van Alphen 2010, Fernandez 2020, Giurca and Metz 2018; Lopez Hernandez 2019; Binz et al. 2014, Rohe and Chlebna 2022), few connect to the theory on network structure (Hermans et al. 2013b; Hermans et al., 2017).

Studies of social networks have long recognized that networks are made up of structural building blocks (Lusher et al. 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 (Granovetter 1973, Burt 2000; Bodin and Tengo 2012). For example, two motifs that have been central in the recent studies of governance networks are open and closed triangles (Berardo and Scholz 2010; Vantaggiato) (Figure 3.1B). These motifs have explicit structural meaning and come by many names (Prell and Skorovitz 2008 ; Levy and Lubell 2018). Open triangles depict one actor connecting two other actors who are otherwise not connected to one another, also referred to as brokerage (Burt 2005) or coordination (Berardo and Scholz 2010). This open triangle configuration, measured by a network's 'centralization', is associated with efficiency and reduced transaction costs, as one actor takes on a centralized leadership role (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) or cooperation (Berardo and Scholz 2010). This cooperation configuration, measured by a network's 'transitivity'/'triadic closure', suggests co-development and exchange of ideas, as well as trust-building and cohesion (Burt 2005, Prell and Lo 2016). While these two structures are not mutually exclusive (Vantaggiato, Levy and Lubell 2018), they serve as foundational structures around which

to build 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 and Markard 2012; Musiolik et al. 2020). 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 theories in innovation systems to social networks, we are able to 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 (e.g. van Alphen 2010, Giurca and Metz 2018; Binz et al. 2014, 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 2013b, Hermans 2017). We propose that inferential network analysis, which statistically tests for the prevalence of different structures and other network attributes compared to randomly generated networks with similar features (Scott and Ulíbarri 2019), can help us test and advance existing innovation system theory regarding networks.

²Further, we believe that the structures observed by Musiolik et al. (2020) are limited based on their 'ego-centric' interview methods (Chung et al 2005) which relied largely on the perspective of key actors and the behavior of system builders. 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 partner mode cases.

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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 theory has developed to identify the conditions predicting different structural configurations (Musiolik et al. 2020; Binz and Truffer 2017). To describe system building, Musiolik et al. (2020) put forth a resource-based approach to predict the two key multi-actor network structures: partner and intermediary modes. They propose that actors pursue different structures based on resource availability and resource concentration within the system. 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.

The resource-based reasoning supporting the system-building theory resembles the logic of other social network theories, particularly those from network governance (Provan and Kenis 2008). Here, 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; Lubell et al. 2017). 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). On the other hand, when the need for network-level competencies is low, networks will take a participant-led approach where actors partner to

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co-create strategic alliances.³ These network governance concepts map well onto Musiolik et al's intermediate and partner modes (2020), and complement them by aligning them with explicit structural motifs (Rudnick, Lubell).

Testing these theories can be challenging because innovation systems are a complex web of several (likely overlapping) networks. Networks are multi-functional (Vantaggiato and Lubell 2022) and 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 (Spielman et al. 2011; Giurca and Metz 2018; Truffer and Binz 2017). The functional purposes of a network connection are not necessarily discrete, especially as the connections become repeated over long-term interaction (Oh et al. 2004, BETTER CITE). 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 (Cholez 2020).

To capture the complexity of innovation 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 capital 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 total

³We 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.

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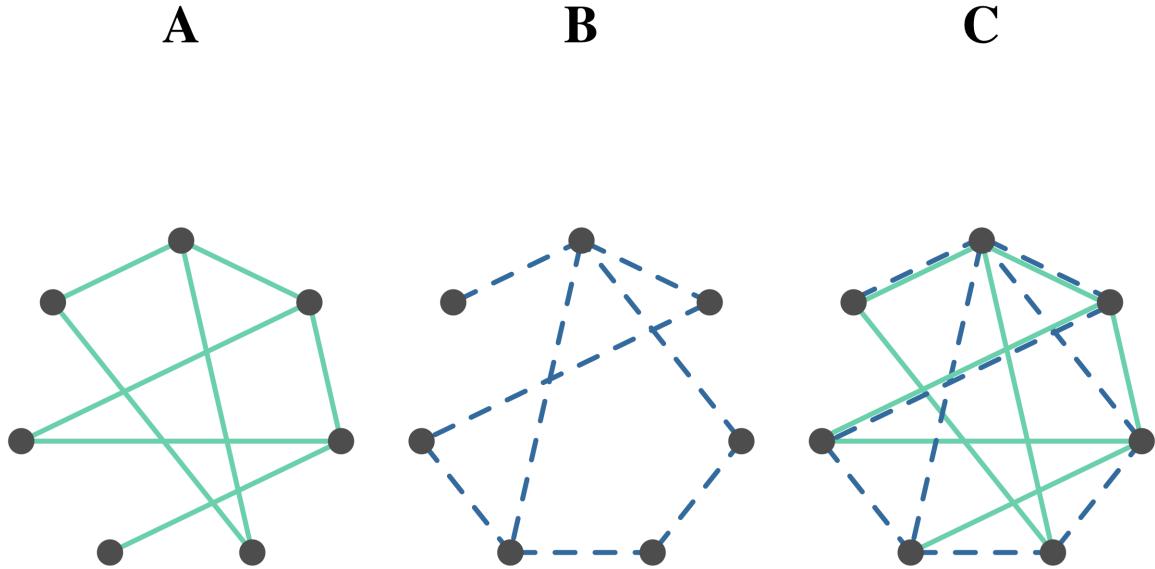


Figure 3.2: A) (left) A subsystem/network to address one kind of system resource deficit (e.g. knowledge development). B) (center) A subsystem to address a second kind of system resource deficit (e.g. market formation). C) (right) The combination of both resource subsystems, which make up a multi-functional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

innovation system network, where the structure of each builds the structure of the whole (Figure 3.2).

{width=“6.5in” height=“2.2745975503062117in”} We use these two resource subsystems – knowledge subsystem and valuation subsystem – as cases for testing the resource-based theory.

H1: Closed triangles/partner mode network structures will be more prevalent in innovation resource subsystems that have existing, decentralized resources

2.2.2 Actor composition variation based on institutional logic

Actor agency is a central motivation for expanding theory on innovation system formation (Musiolik and Markard 2011; Kern 2015). For example, research on 'system builders' identifies prime movers who create cohesion and direction within an innovation system (Hellsmark and Jacobsson 2009; Musiolik et al. 2020). These system builders contrast from 'complementary actors', who seem generally passive in their network activity (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 (Hermans et al. 2013, Van Alphen 2010; Binz et al. 2014, Lamers et al. 2017). In short, we ask: What 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

⁴We choose to focus on actor categories rather than a existing classification of 'system builders' for three reasons. First, classifying system builders seems to have little formula: 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 largely relational, and therefore this dynamic of coordinating and/or bridging will still come through in the results based on our network approach, allowing us to still include system building in our discussion. 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 and is therefore a collective process (Musiolik et al. 2020), 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 3).

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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, respectively (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 et al. 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). Examples from the privatization of agricultural extension also strengthen this point, finding that private control of knowledge development and outreach tend to fall short to publicly managed models (Eastwood et al. 2017; Labarthe and Laurent, 2013). 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 (van Alphen 2010; Binz et al. 2014).

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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 et al. 2012), and so processes like resource acquisition and developing business relationships better align with their incentive structures. 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 resource 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 behavioral and 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, Seivers-Glotzbach 2020/Rohe forever niche), 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 in the

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US are described in Chapter 1 and Chapter 2, as well as in X and Y for an international context.

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 et al. 2012).

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 develop the innovation and shape the system, but membership can be transient (e.g. conference attendees), and whether this is strategic or emergent (Musiolik et al. 2020) is hard to delineate.

Recent theory has focused on formal networks, given that they are venues for strategic system building (Musiolik et al. 2020; Cholez and Marie-Benoit 2023). 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 (Klerkx and Proctor; Cholez and Marie-Benoit 2023), informal exchanges may at some point become formalized (CITE), 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 (Van de Ven, Musiolik et al, 2020). 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

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

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

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 et al. 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% (247/756). 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-1.

3.2 Challenges and expertise as system resources

We measure the presence 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

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and valuation resources and represent a unique issue (full list is available in Appendix C-2). 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: 1 – no challenge, 2 – somewhat of a challenge, 3 – moderate challenge and 4 – serious challenge. For expertise, the scale represented: 1 – no expertise/not my work, 2 – low expertise/rarely work on, 3 – moderate expertise/sometimes work on, and 4 – strong expertise/often work on. Based on these survey questions we are able to compare the challenges and expertise in the organic seed network 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 et al. 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 types of relationships to the functional and resource-based frameworks combined by Binz et al. (2016). The knowledge resource subsystem includes connections related to information acquisition and exchange, research partnerships, stakeholder involvement in projects, and academic collaborations. The valuation resource subsystem combines the resource mobilization and market formation functions, which includes seed acquisition, seed ex-

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

Functional.subsystems	Resource.subsystems	Types.of.relationships
Knowledge	Knowledge creation	Information acquisition and exchange, Research par-
Valuation	Resource mobilization	Seed acquisition, seed exchange, research funding
Valuation	Market formation	Licensing agreements, contracts, rent, buy, and/or s

change, 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 based on project or organization co-participation, as is common in other innovation network studies (Hermans 2013a; van alphen 2010, Binz et al. 2014). 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, as is the case with networks derived from co-participation (Berardo and Scholz). Instead, this approach allows connections to be defined based on actors' own perceptions of a relationship. Second, there are challenges to analyzing two-mode data (i.e. actor-to-project) with traditional network methods (Jasny), which we bypass by collecting one-mode data (i.e. 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 1208 ties between 645 uniquely identifiable nodes. Based on data from the survey and supplementary seed stakeholder databases, we added actor-type and geographic attributes to each stakeholder in our network. We label the actors by their role based on the types outlined by the multi-actor perspective (Avelino and Wittmeyer). The initial groupings based on these typologies are: state, firm, third sector (non-governmental organizations), and research. We then

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divide the actors in our research category into government agency actors and public university actors because we argue that university researchers have their own institutional logic (Leydesdorff). We also divide the 'firm' category into seed producers and companies. Although they are both actors under the private institutional logic, we argue that producers (and farmers generally) are a blend between for-profit and community logics, as their occupation is often linked to their identity, place, and a particular value set (Thompson et al. 2015). As a result, our actor groups and their institutional logics are as follows: Seed producers (firm-community hybrid), seed processors and retails (firms), governmental agencies (state) and universities (state-community hybrid), and non-governmental organizations (third sector). 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 resource subsystems, we employ two Exponential Random Graph Models (ERGMs) (Lusher et al. 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 et al. 2012). Endogenous predictors are the structural 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 actors in the network – referred to in network terminology as 'nodes' – which in this analysis include the actor types and 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 (Prell

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2012).

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 (Levy 2016; Ready and Power 2020). 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 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 (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 resource subsystem and a positive parameter value for company actors in the valuation resource subsystem.

⁵Note that this parameter is often misinterpreted in studies that use ERGMs and we encourage readers with further interest to explore more in the following resources: [\[https://figshare.com/articles/poster/Interpretation_of_GW-Degree_Estimates_in_ERGMs/3465020\]](https://figshare.com/articles/poster/Interpretation_of_GW-Degree_Estimates_in_ERGMs/3465020)

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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).

NEED TO PUT IN TABLE3

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 ‘statnet’ (Krivitsky et al. 2022) software package. All analysis was conducted using R statistical software and code is available AT FINAL LINK. Model building and selection is available in Appendix C-3.

4. Results

4.1 Organic seed system resource deficits

The organic seed system has been developing now for over twenty years (Chapter 1, Hubbard et al. 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 man-

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aging 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 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."

Between the two types of resources, 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.{width="6.5in" height="3.652777777777777in"}
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 particularly high on knowledge-related topics, such as identifying key traits, controlling weeds, soil fertility, and disease pressure. There is also low to moderate expertise available on valuation topics like developing infrastructure, finding high quality seed stock, and accessing capital.

Between the two types of resources, 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

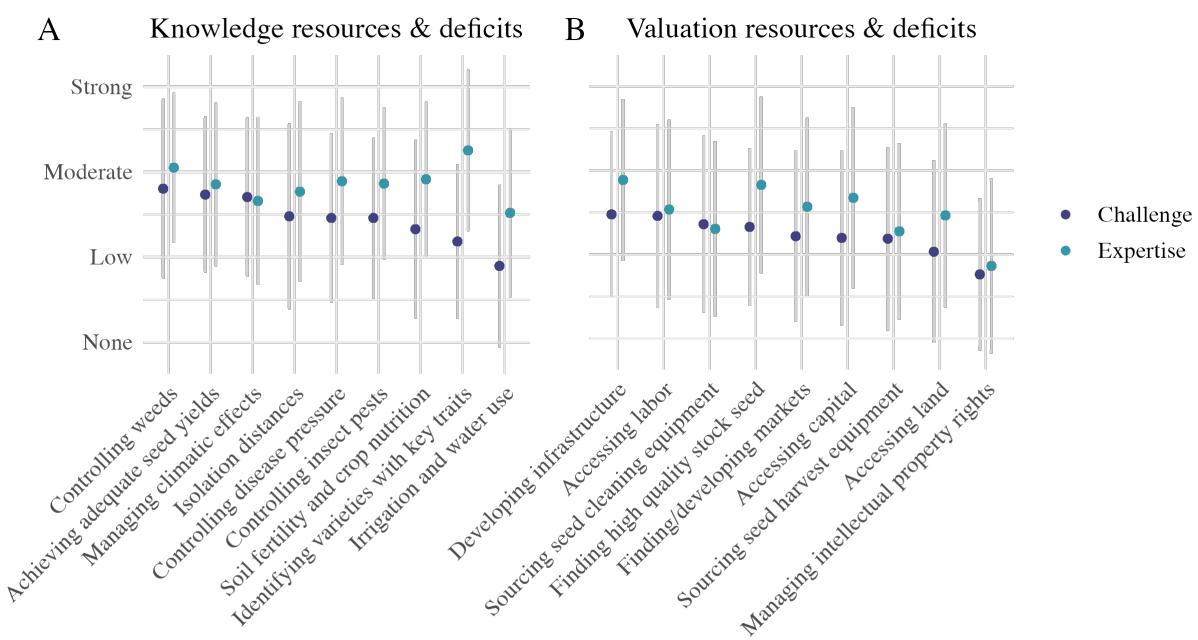


Figure 3.3: Ratings of challenges (purple) and expertise (blue) for topics related to A. Knowledge resources and B. Valuation resources. Points represent the mean score from respondents 1-4 ratings (challenge n=144, expertise n=104) and gray bars represent the standard deviation from the mean.

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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 see that the strength of expertise by researchers and organizations is higher than the magnitude of challenges perceived 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, expertise related to valuation resources score 0.3 points higher than challenges related to valuation resources and 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. [Author's] book comes up fairly short on this. [Organization] has almost nothing for one of the most critical attributes for quality seed production.*" 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 of the partner mode in accordance with resource availability. Between the two subsystems, however, we observe that the availability of valuation resources (expertise) is lower than knowledge resources. 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 how much the connections in the graph are organized around central/focal points, 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 extension and government actors together account for the remaining fifth. Representations

4. RESULTS

Table 3.3: Descriptive summaries of the innovation system network and resource subsystems

X.	Innovation.system	Knowledge	Valuation
Actors	645	522	418
Connections	1908	1106	802
Avg. # connections	5.92	4.24	3.84
Density	0.006	0.006	0.007
Transitivity	0.09	0.09	0.06
Centralization	0.1	0.12	0.08
Producers	125 (19%)	101 (19%)	92 (22%)
Company	208 (32%)	146 (28%)	177 (42%)
Organization	190 (29%)	171 (33%)	86 (21%)
University & extension	73 (11%)	73 (14%)	33 (8%)
Government	49 (8%)	31 (6%)	30 (7%)

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. Across nearly all 'slices' of the system, the networks are mostly 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

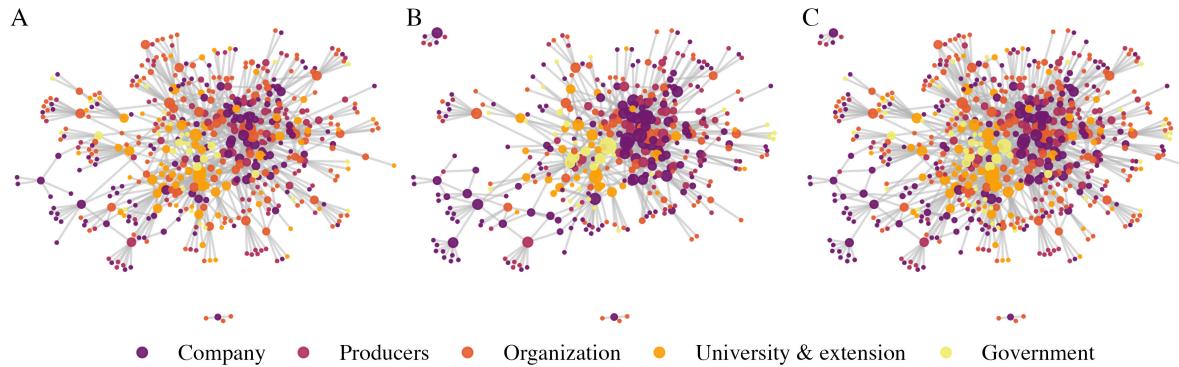


Figure 3.4: The resource subsystems of the organic seed innovation system. A) Knowledge subsystem, B) Valuation subsystem and C) Whole innovation system. Circles in the graph represent actors/organizations and lines represent connections based on the different relationships within each subsystem. Nodes 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).

network analysis to elaborate on the relationship between structure and resource needs in innovation systems.

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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

4. RESULTS

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 model results is available in Appendix C-4.

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, and so we expect that both subnetworks will show 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: 5.31, SE: 0.52 ; valuation: 4.34, SE: 0.47). Similarly, for the transitivity parameter we observe positive and significant coefficient estimates for both resource subsystems (knowledge: 0.77, SE: 0.06 ; valuation: 0.4, SE: 0.06).

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 transitivity term, the odds of a tie between two actors with a shared partner are 116% greater than the odds of a tie between two actors with no shared partners in

CHAPTER 3. NETWORK FORMATION

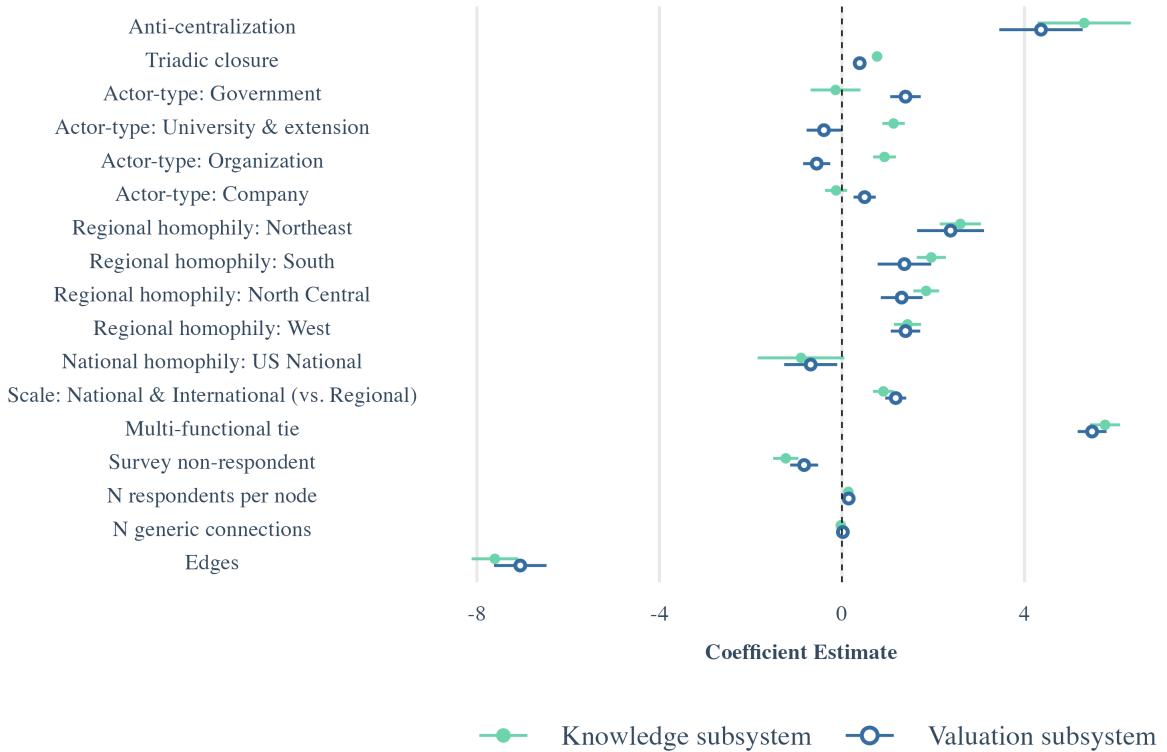


Figure 3.5: Coefficient plot for the ERGMs of the knowledge (dark purple, closed circles) and valuation (blue, open circles) subsystems. Each point represents the value of the coefficient estimate (reported as log-odds) and bars represent the confidence intervals surrounding each estimate. Values with confidence intervals fully on either size of zero are considered significant.

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 31% 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 ties with a few central, coordinating actors, actors are building more diffuse relationships for cooperative, partnered relationships.

{width=“6.5in” height=“4.33333333333333in”} When comparing the structures of the knowledge and valuation subsystems to one another, we observe some variation that lends

4. RESULTS

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 116% greater than the odds of a tie between two actors with no shared partners in the knowledge subsystem, these odds decrease to 50% in the valuation subsystem. Likewise, actors in the knowledge subsystem are 37% less likely to form a tie with a popular, coordinating actor, in contrast from the 31% lower likelihood in the valuation subnetwork.

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 1.13 (SE 0.13) and 0.92 (SE 0.13) respectively. Converting these estimates into odds, the odds of these actors' forming a tie is 210% (university) and 153% (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 0.6 (SE 0.12) and 1.45 (SE

0.17) respectively. In other words, the odds of these actors forming a tie is 88% (companies) and 327% (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 -0.47 (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 us 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 () – 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.

Though this work is among the first to empirically test conditions predicting network structure in the innovation systems literature (Binz, Cholez), we draw on social network and network governance fields to quantify and contextualize these results in related disciplines (). 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 (Provan and Kenis, Lubell, Rudnick). When there are network-level resources required, such as building

5. DISCUSSION

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 (Provan and Kenis, Jones). Some of these have been theorized and explored, such as the customization of products affecting structure across spatial scales(Binz and Truffer, Chapter 2), and how trust and network size change over time (Hermans 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 analysis, including methods like conditional uniform graph tests, exponential random graph models, and autologistic actor attribute models (Robins), as an approach for rigorously testing network building theory (Scott and Ulíbarri).

5.2 Actor composition aligns with logic 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 hypotheses defined by the multi-actor perspective (). We find that non-profit actors like organizations and universities are significantly more active in the knowledge resource subsystem, while for-profit companies

CHAPTER 3. NETWORK FORMATION

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/Auti). These results help us better understand what it means to be a 'system builder' (Musiolk). In short, system builder profiles likely change based on the kinds of resources that are being generated (Leysdorff). Activity is likely to be higher among actors whose incentive structures align with the system resources being created in the network.

Alignment between institutional logic and resource subsystem met our expectations for all of the actor types except government. Rather than fitting cleanly into the role of public actor with a pre-competitive logic, governments played a blended role. Governmental actors and organizations 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 (MAP/Leysdorff), these results make sense in the context of a niche innovation system (Raven). Because niches are often not yet competitive in their own right, the government often plays a nurturing role to support traditionally private functions (Raven). 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 poli-

5. DISCUSSION

cymakers 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. (2020) where 'a system builder coordinates activities in a network of collaborators to develop new, intermediate organizational structures' (p. 10). We believe this aligns best with Provan and Kenis's 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' (Table 2, p. 9) where 'system resource build-up is demanding' (Table 3, p. 11). Other theoretical perspectives, such as the risk hypothesis in policy network literature (Berardo and Scholz 2010), associate these features with closed triangle structures.

Furthermore, there is no clear definition of resource deficit in the resource-based literature (), and so our operationalization of this concept 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 sought to understand the conditions predicting innovation system network formation and actor composition. We test existing theories about resource-based innovation networks (Musiolik) and actor logics (Avelino) by connecting to social network theory and methods (Provan and Kenis, Robins). We used the case of the organic seed innovation system, which we divided into two resource subsystems representing knowledge and valuation functions, both of which have existing but dispersed resources. Exponential Random Graph Modeling helped us statistically test the likelihood of tie formation to describe different network building processes and relative actor involvement. These models show support for the developing 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 as that function better aligns with the pre-competitive logic of public institutions. On the flip side, private actors are generally more engaged in building valuation resource subsystems.

STILL DRAFTING. As described by Musiolik et al. (2012), these contributions are useful because "in order to better understand and improve system performance, we have to look into the processes through which technological innovation systems are intentionally created" (p. 1034). Still, we need to continue to test theory using comparable methods... Connecting with parallel literature like network governance and policy networks can help ground the theory and show rigorous methods for testing.

Conclusion

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More info

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Appendix A

Appendix A

- 1. Model selection and fit**
- 2. Full model results**
- 3. Predicted conventional seed use for field and forage crop growers**

3. PREDICTED CONVENTIONAL SEED USE FOR FIELD AND FORAGE CROP GROWERS

Table A.1: Model comparison results

Term	Model 1		Model 2		Model 3		Model 4		Model 5	
	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

APPENDIX A. APPENDIX A

Table A.3: Full model results

Term	Mean estimate	Standard error
(Intercept)	-0.663	0.002
Southern region (vs. North Central)	0.124	0.003
Northeastern region (vs. North Central)	0.236	0.002
Western region (vs. North Central)	0.351	0.002
Vegetable crops (vs. Field)	0.214	0.002
Forage crops (vs. Field)	0.848	0.002
Certifiers request organic seed use	0.043	0.001
Seed saved or traded (%)	-0.096	0.001
Crop diversity	-0.065	0.001
Farm size (acres)	0.114	0.001
Values organic seed	-0.200	0.001
Year: 2020 (vs. 2010)	-0.334	0.002
Year: 2015 (vs. 2010)	-0.171	0.002
Barrier: Insufficient quantity	0.009	0.001
Barrier: Buyer requirements	0.112	0.001
Barrier: Undesirable traits	0.127	0.001
Barrier: Organic availability	0.140	0.001

3. PREDICTED CONVENTIONAL SEED USE FOR FIELD AND FORAGE CROP GROWERS

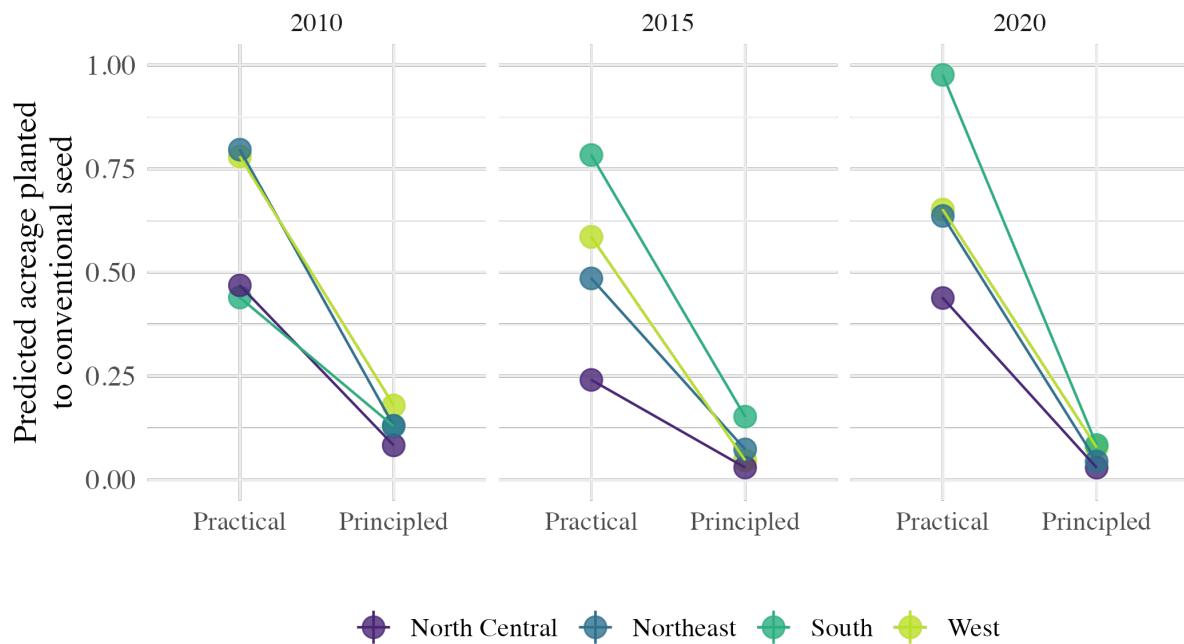


Figure A.1: Predicted mean estimates for field crop growers of two farmer profiles.

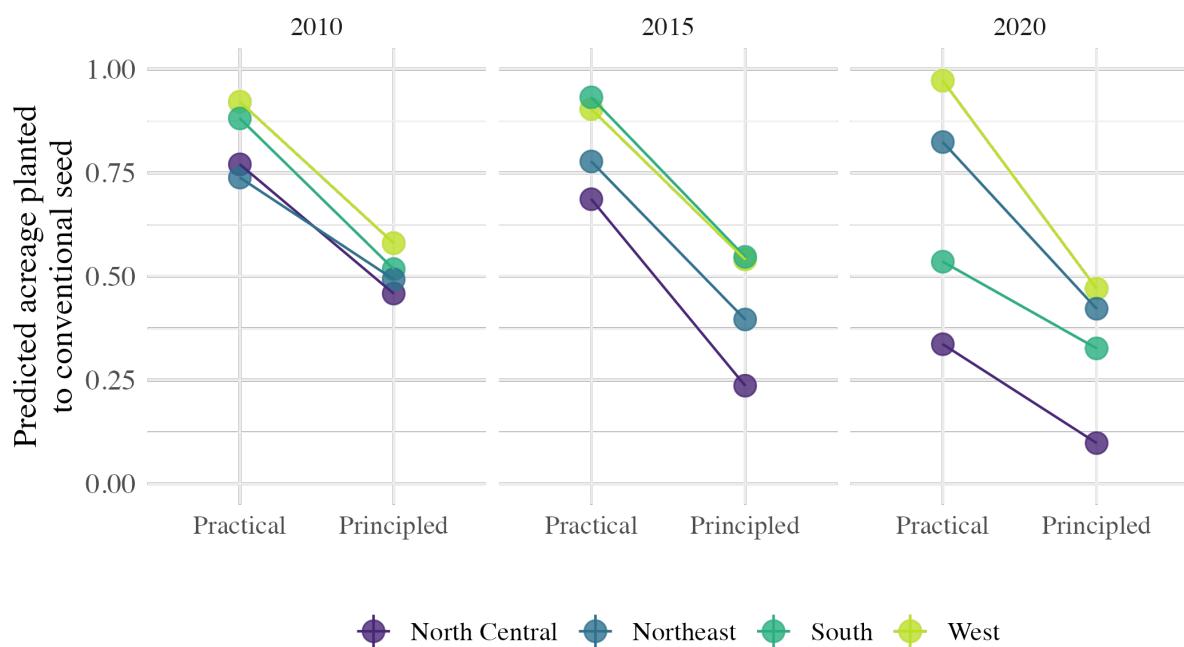


Figure A.2: Predicted mean estimates for forage crop growers of two farmer profiles.

Appendix B

Appendix B

1. Selecting spatial terms

We further explore space's influence on tie formation by comparing the 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 defined regional 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, we assign the mean geodesic distance. Our model shows a significant negative relationship between distances and likelihood of connection, suggesting that connections are not made only from convenience of distance. Instead, actors seek others who have relevance to the resources they need, but still in the regional context that they need it. Second, we run the model using 12 Plant Hardiness Zones outlined by the USDA, rather than the four administrative regions. These PHZs help zoom in on more specific similarities across

2. DEFINING ACTORS' SPATIAL SCALES

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

Term	Knowledge subsystem		Valuation subsystem	
	Estimate	SE	Estimate	SE
Spatial distance (log)	-0.081	0.027	0.062	0.045
Scale: National (vs. Regional)	-0.096	0.109	0.657	0.066
Other subsystem structure	5.273	0.134	0.326	0.360
Anti-centralization	4.997	0.497	3.682	0.406
Triadic closure	0.964	0.062	0.802	0.058
Edges	-4.689	0.387	-6.091	0.660
Survey non-respondent	-1.170	0.142	-1.104	0.107
N respondents per node	0.280	0.026	0.121	0.027
N generic connections	-0.090	0.017	0.025	0.010
Fixed -Inf	-Inf	0.000	-Inf	0.000

space regarding growing needs. We do not have PHZ for Canada, and so we look for the nearest USDA PHZ and assign it to them. 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. We compare the model fit of these three approaches and find best fit for the four-region model, presented in Appendix C-3 and Figure 2.3

2. Defining actors' spatial scales

3. Full model results.

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

Term	Knowledge subsystem		Valuation subsystem	
	Estimate	SE	Estimate	SE
PHZ homophily: Zone 3	2.819	1.226	2.518	0.895
PHZ homophily: Zone 4	1.729	0.250	1.141	0.255
PHZ homophily: Zone 5	1.459	0.171	0.703	0.197
PHZ homophily: Zone 6	0.921	0.180	0.886	0.158
PHZ homophily: Zone 7	1.093	0.270	1.445	0.246
PHZ homophily: Zone 8	0.946	0.155	1.280	0.120
PHZ homophily: Zone 9	1.161	0.352	0.690	0.364
PHZ homophily: Zone 10	1.405	0.855	2.447	0.338
Scale: National (vs. Regional)	0.039	0.094	0.696	0.066
Other subsystem structure	5.170	0.188	0.390	0.406
Anti-centralization	5.041	0.465	3.742	0.433
Triadic closure	0.921	0.065	0.757	0.062
Edges	-6.267	0.161	-5.435	0.128
Survey non-respondent	-1.163	0.133	-1.250	0.112
N respondents per node	0.303	0.029	0.137	0.034
N generic connections	-0.072	0.015	0.028	0.010
Fixed -Inf	-Inf	0.000	-Inf	0.000

Table B.3: Model comparison results

Model	Knowledge subsystem		Valuation subsystem	
	BIC	AIC	BIC	AIC
Geodesic distance	6179	6090	6590	6505
Plant Hardizess Zones	6070	5913	6565	6415
SARE Regions	5855	5727	6377	6255

3. FULL MODEL RESULTS.

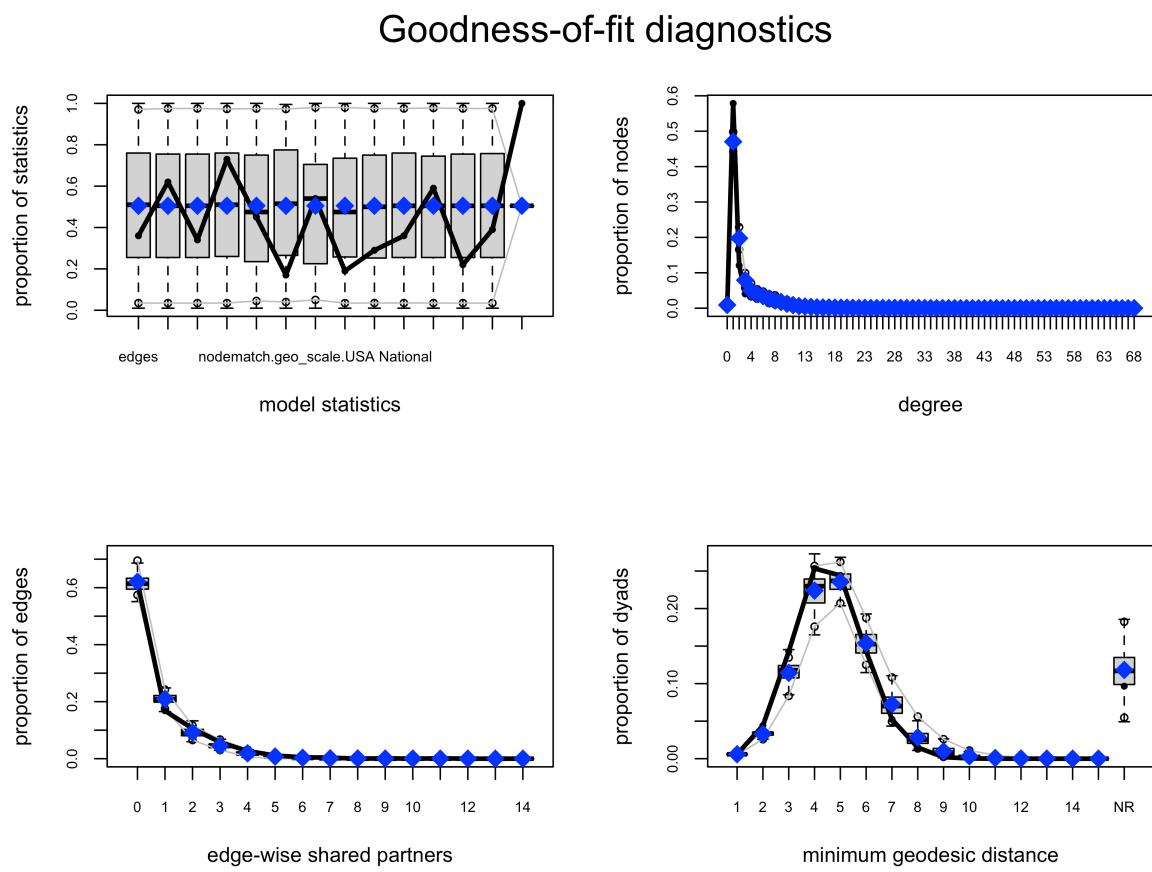


Figure B.1: Knowledge resource subsystem ERGM goodness of fit plots

Goodness-of-fit diagnostics

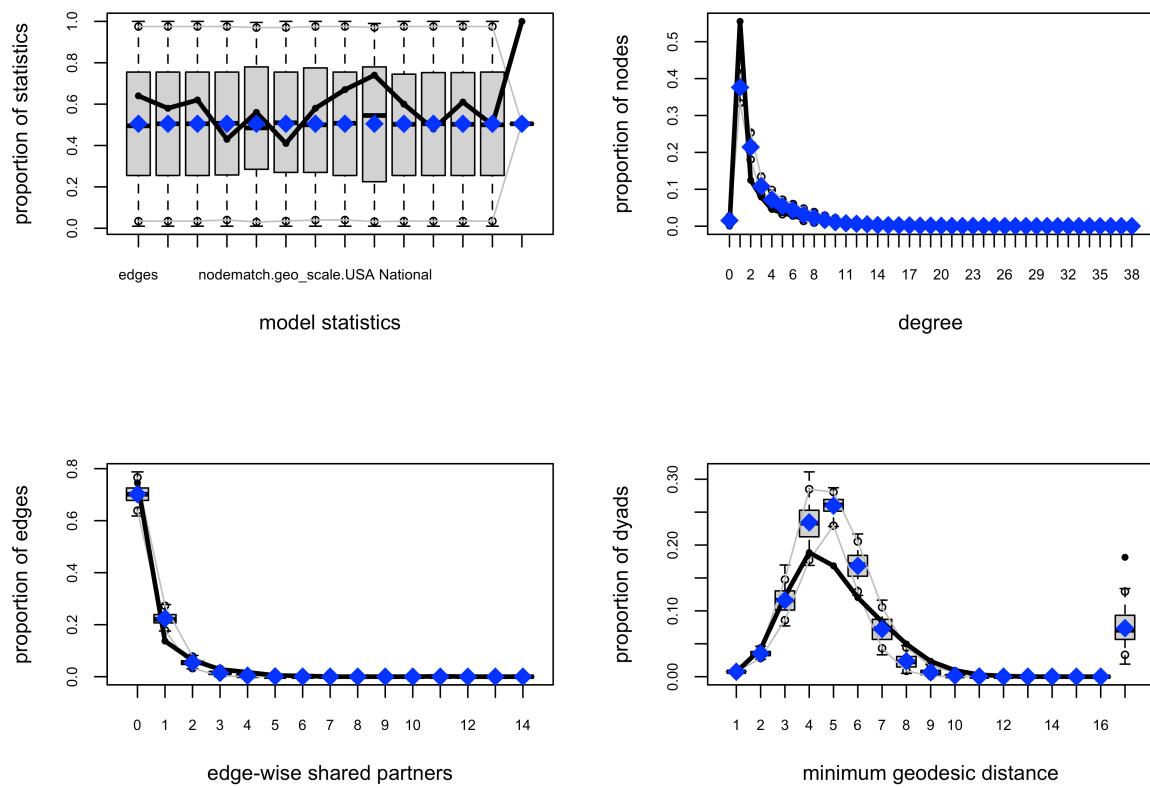


Figure B.2: Valuation resource subsystem ERGM goodness of fit plots

3. FULL MODEL RESULTS.

Table B.4: Full model results: SARE regions

Term	Knowledge subsystem		Valuation subsystem	
	Estimate	SE	Estimate	SE
Regional homophily: Northeast	2.612	0.184	2.475	0.212
Regional homophily: South	1.940	0.158	1.969	0.188
Regional homophily: North Central	2.090	0.150	1.676	0.177
Regional homophily: West	1.076	0.146	1.518	0.132
National homophily: US National	-0.938	0.399	-0.916	0.272
Scale: National (vs. Regional)	0.735	0.122	1.389	0.092
Other subsystem structure	5.135	0.137	0.357	0.378
Anti-centralization	5.097	0.510	3.885	0.428
Triadic closure	0.864	0.058	0.763	0.056
Edges	-6.587	0.170	-5.989	0.153
Survey non-respondent	-1.175	0.146	-1.103	0.112
N respondents per node	0.278	0.030	0.129	0.029
N generic connections	-0.078	0.017	0.029	0.009
Fixed -Inf	-Inf	0.000	-Inf	0.000

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

Location	Producer			Company			Researcher			Organization			
	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

1. SAMPLE REPRESENTATIVENESS ACROSS US REGIONS AND SPATIAL SCALES

Appendix C

Appendix C

1. Sample representativeness across US regions and spatial scales

2. Full list of 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 – redundancy with Achieving adequate seed yields Adapting to climate change – redundant with Managing climatic effects Managing pollinator habitats – too niche for many responses Vernalization for biennial crops – too niche for many responses Overwintering for biennial crops – too niche for many responses In-field seed production costs – irrelevant to knowledge or valuation resources Harvest costs – irrelevant to knowledge or valuation resources Seed cleaning costs – irrelevant to knowledge

APPENDIX C. APPENDIX C

Table C.2: ERGM comparison for knowledge resource subsystem

Coefficient	Model1	Model2	Model3	Model4	Model5
Anti-centralization		4.89*** (0.46)	4.91*** (0.68)	NA (NA)	5.31*** (0.52)
Triadic closure		1.27*** (0.04)	0.8*** (0.07)	NA (NA)	0.77*** (0.06)
Actor-type: Government				NA (NA)	-0.14 (0.28)
Actor-type: University & extension				NA (NA)	1.13*** (0.13)
Actor-type: Organization				NA (NA)	0.93*** (0.13)
Actor-type: Company				NA (NA)	-0.13 (0.12)
Regional homophily: Northeast			2.67*** (0.32)	NA (NA)	2.6*** (0.23)
Regional homophily: South			2.52*** (0.35)	NA (NA)	1.96*** (0.16)
Regional homophily: North Central			2.18*** (0.26)	NA (NA)	1.85*** (0.14)
Regional homophily: West			1.3*** (0.26)	NA (NA)	1.44*** (0.15)
National homophily: US National				-1.23** (0.61)	NA (NA)
Scale: National & International (vs. Regional)				0.89*** (0.19)	NA (NA)
Multi-functional tie				5.44*** (0.19)	5.77*** (0.17)
Survey non-respondent		-1.37*** (0.1)	-1.31*** (0.23)	NA (NA)	-1.23*** (0.14)
N respondents per node		0.18*** (0.01)	0.29*** (0.06)	NA (NA)	0.14*** (0.04)
N generic connections		-0.01 (0.01)	-0.08*** (0.03)	NA (NA)	-0.03 (0.02)
Edges	-5.11*** (0.04)	-5.49*** (0.1)	-6.68*** (0.28)	NA (NA)	-7.61*** (0.26)
Fixed -Inf		-Inf*** (0)	-Inf*** (0)	-Inf*** (0)	-Inf*** (0)
BIC	9978	8149	5817	7584	5648

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 – irrelevant to knowledge or valuation resources Contamination from GE crops – irrelevant to knowledge or valuation resources

3. Model building and selection

First, selecting decay parameters will full model. The models do not converge when running several all the possible iterations. So first I run a range of `gwdegree` decay values with a `gwesp` decay value = 0.5. Then based on the best-performing `gwdegree` decay value (alpha = 0.1), I run a range of `gwesp` decay values. Based on decay values of 0.7 (knowledge) 0.9 (valuation), I compare different builds of the model. For the full

3. MODEL BUILDING AND SELECTION

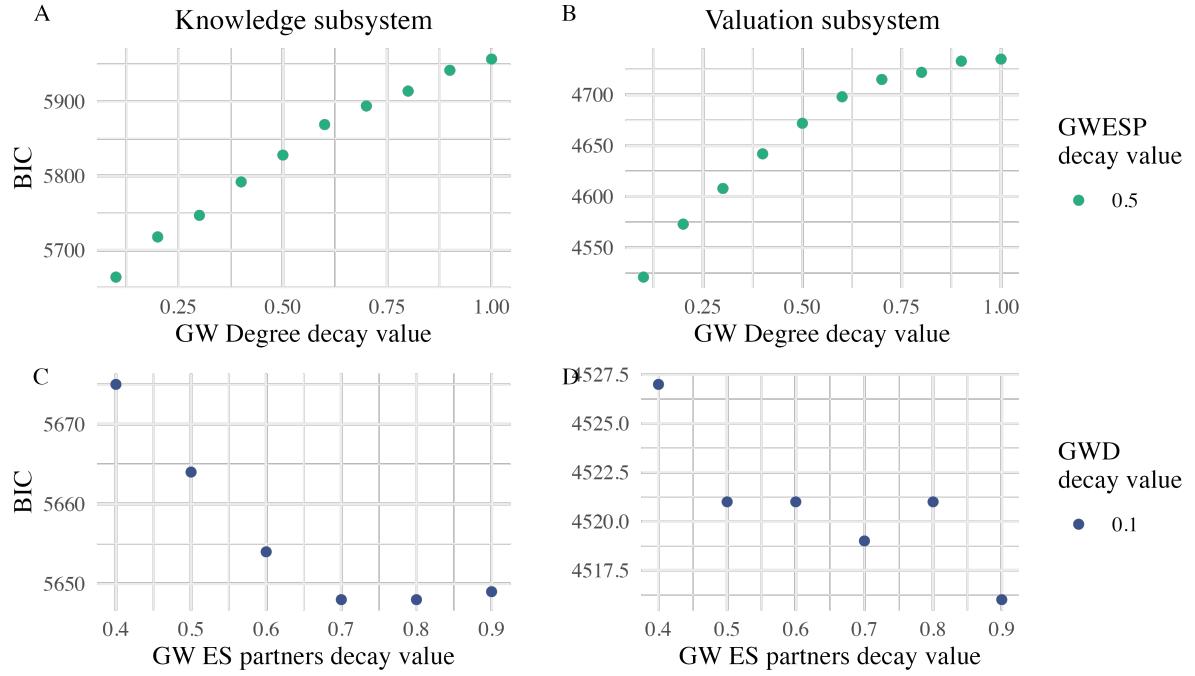


Figure C.1: BIC values across different ERGM geometrically weighted decay value specifications

Table C.3: ERGM comparison for valuation resource subsystem

Coefficient	Model1	Model2	Model3	Model4	Model5	
Anti-centralization		3.62*** (0.41)	3.81*** (0.42)	NA (NA)	4.36*** (0.47)	
Triadic closure		0.95*** (0.03)	0.35*** (0.06)	NA (NA)	0.39*** (0.06)	
Actor-type: Government				NA (NA)	1.39*** (0.17)	
Actor-type: University & extension				NA (NA)	-0.4** (0.19)	
Actor-type: Organization				NA (NA)	-0.55*** (0.15)	
Actor-type: Company				NA (NA)	0.5*** (0.12)	
Regional homophily: Northeast			2.5*** (0.34)	NA (NA)	2.38*** (0.37)	
Regional homophily: South			1.34*** (0.28)	NA (NA)	1.37*** (0.3)	
Regional homophily: North Central			0.9*** (0.24)	NA (NA)	1.31*** (0.23)	
Regional homophily: West			1.43*** (0.17)	NA (NA)	1.39*** (0.16)	
National homophily: US National				-0.5 (0.35)	NA (NA)	-0.68** (0.3)
Scale: National & International (vs. Regional)				1.25*** (0.12)	NA (NA)	1.18*** (0.12)
Multi-functional tie				5.23*** (0.12)		5.48*** (0.16)
Survey non-respondent		-0.98*** (0.1)	-0.49*** (0.16)	NA (NA)	-0.83*** (0.16)	
N respondents per node		0.07*** (0.02)	0.02 (0.06)	NA (NA)	0.15** (0.07)	
N generic connections		0.02*** (0.01)	0.04*** (0.01)	NA (NA)	0.02 (0.01)	
Edges	-4.9*** (0.04)	-4.95*** (0.09)	-6.53*** (0.22)	NA (NA)	-7.05*** (0.29)	
Fixed -Inf		-Inf*** (0)	-Inf*** (0)	-Inf*** (0)	-Inf*** (0)	
BIC	7606	6651	4643	6384	4516	

Goodness-of-fit diagnostics

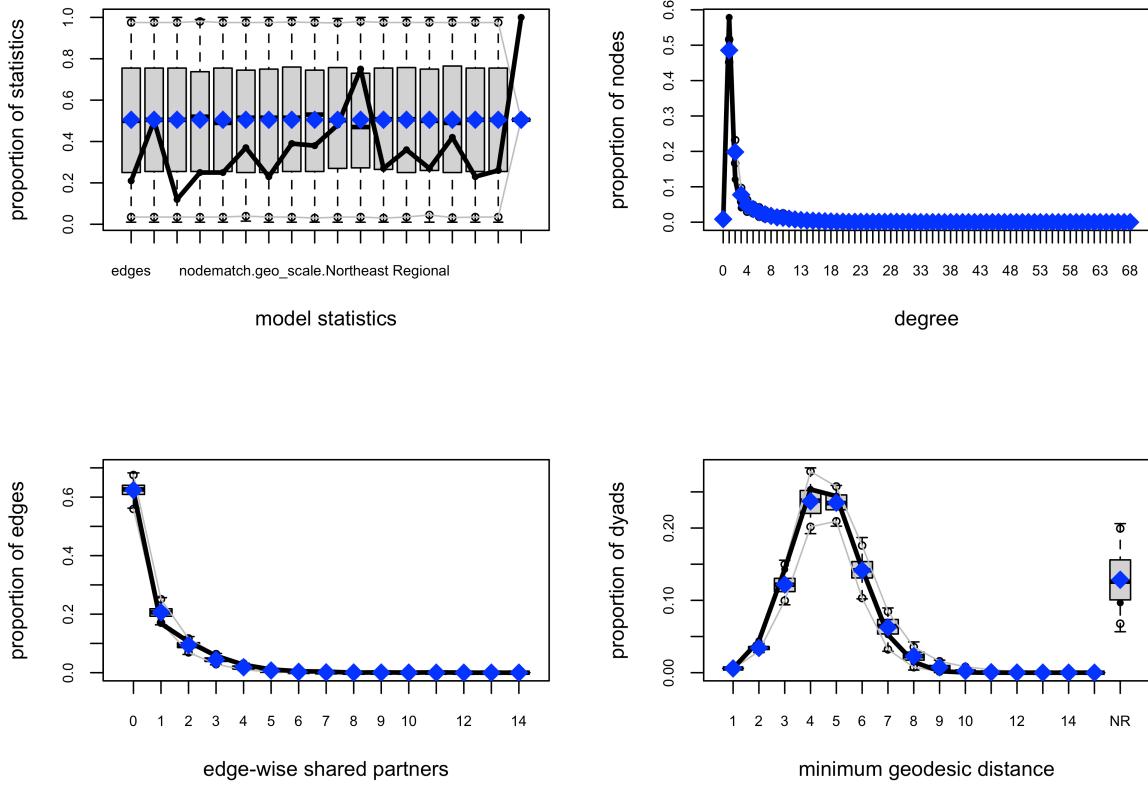


Figure C.2: Knowledge resource subsystem ERGM goodness of fit plots

and final model, with decay values of gwdegree alpha = 0.1 and gwesp alpha = 0.9, we can look at goodness-of-fit plots.

4. Full model results

4. FULL MODEL RESULTS

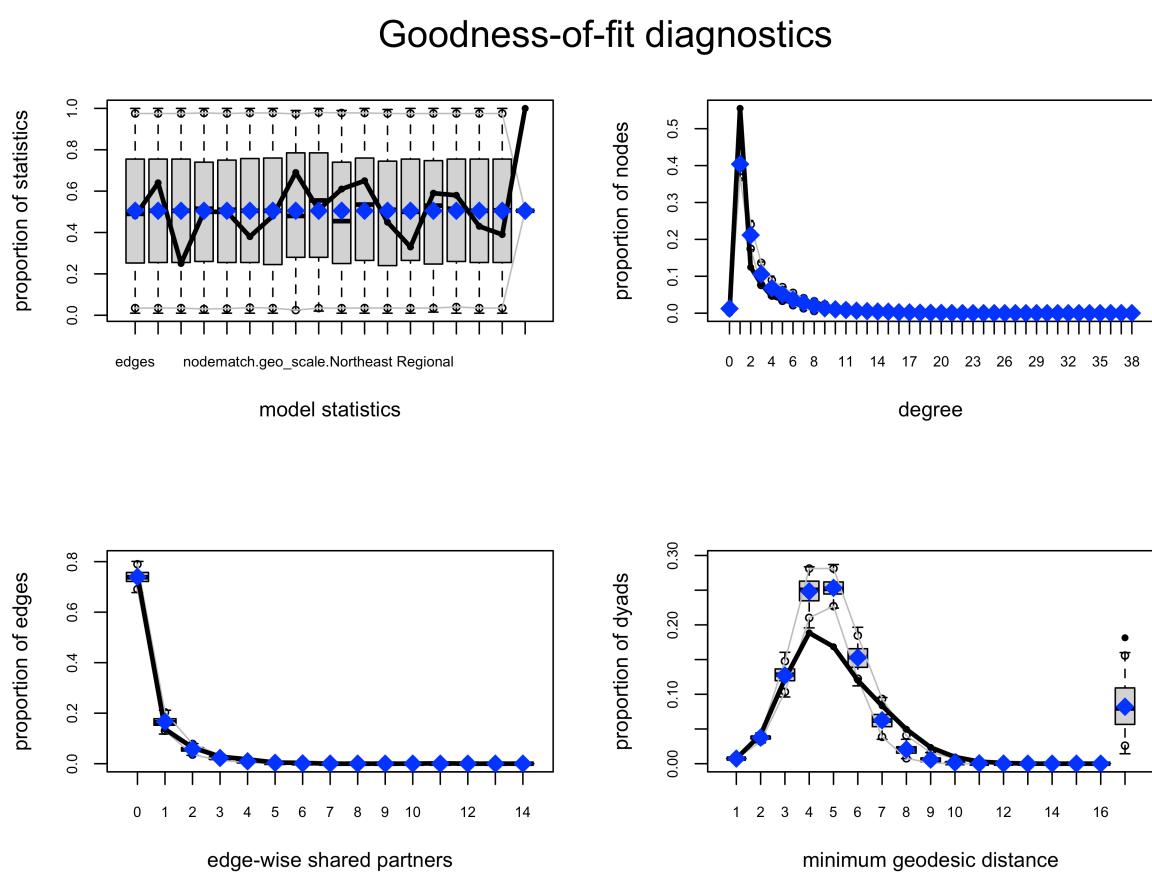


Figure C.3: Valuation resource subsystem ERGM goodness of fit plots

APPENDIX C. APPENDIX C

Table C.4: Full model results

Term	Knowledge subsystem		Valuation subsystem	
	Estimate	SE	Estimate	SE
Anti-centralization	5.309	0.521	4.363	0.466
Triadic closure	0.769	0.059	0.389	0.056
Actor-type: Government	-0.140	0.279	1.393	0.171
Actor-type: University & extension	1.131	0.126	-0.395	0.194
Actor-type: Organization	0.932	0.127	-0.553	0.152
Actor-type: Company	-0.129	0.124	0.497	0.124
Regional homophily: Northeast	2.596	0.230	2.381	0.374
Regional homophily: South	1.958	0.163	1.369	0.299
Regional homophily: North Central	1.846	0.143	1.309	0.233
Regional homophily: West	1.436	0.152	1.393	0.165
National homophily: US National	-0.898	0.484	-0.685	0.297
Scale: National & International (vs. Regional)	0.908	0.116	1.179	0.117
Multi-functional tie	5.767	0.168	5.483	0.161
Survey non-respondent	-1.231	0.141	-0.829	0.156
N respondents per node	0.140	0.038	0.148	0.070
N generic connections	-0.026	0.016	0.020	0.015
Edges	-7.607	0.260	-7.050	0.294
Fixed -Inf	-Inf	0.000	-Inf	0.000

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.

References

Placeholder

- Bergek, Anna. 2008. “Analyzing the Functional Dynamics of Technological Innovation Systems: A Scheme of Analysis.” *Research Policy* 37(3): 407–29.