RESEARCH ARTICLE

Portraying the Structure and Evolution of Polycentricity via Policymaking Venues

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This paper portrays a polycentric governance system by exploring the evolution of its structure and the interdependencies of its policymaking venues. It utilizes a semi-automated approach developed from the institutional grammar to analyze four policymaking venues by their 55 public policies adopted from 2007 through 2019 in the context of oil and gas development in Colorado, USA. The results show that this governance system continuously evolves through the adoption of public policies, which modifies its constellation of actors, issues, rules, and deontics (i.e., imperatives). In analyzing the content of these policies, we show how the four policymaking venues display interdependencies as well as distinct emphases. The conclusion summarizes the contributions and raises challenges for advancing knowledge about polycentricity.

Keywords: Fracking; Institutional Grammar Tool; Institutional Analysis and Development Framework; Policy Change

Introduction

As a concept, polycentricity describes the extent to which governance systems have multiple independent centers of decision-making authority that interconnect in various ways (Ostrom et al., 1961). Emerging in the late 1950s and 1960s, polycentricity became an image of governance that provided an alternative to the more centralized or monocentric image common at the time. Researchers have since agreed that polycentricity characterizes all governance systems in various forms and degrees (Berardo and Lubell, 2019). At a basic level, polycentricity remains a central concept for understanding governance systems because it provides a lens for assessing and informing the provision and production of public goods and services (Ostrom, 2010). By enabling better fit between governance systems and contexts, polycentricity has the potential to improve capacities for adaptation and responsiveness to problems, leading to better overall performance in governance systems (Carlisle & Gruby, 2017). However, we cannot assume that all polycentric systems perform well, or that they are equivalent in structure and design. To assess and compare governance performance, scholars need to be able to first unpack the structure of different polycentric systems.

Two challenges block our ability to assess polycentric governance systems. The first involves the inconsistent conceptualization and measurement of polycentricity (Heikkila and Weible, 2018). Studies of polycentricity, for example, struggle in defining and operationalizing key terms, from the meaning of interconnections to what constitutes decision-making authorities. The second involves the lack of available longitudinal data and means to capture the dynamic characteristics of polycentric governance systems (Thiel et al., 2019). As a result, the polycentricity literature tends to feature more cross-sectional studies (e.g., Berardo and Lubell, 2016) than longitudinal studies (e.g., Morrison 2017; Carlisle & Gruby, 2018).

To address these two challenges, we develop a semi-automated approach to portray a polycentric governance system of policymaking venues through a systematic analysis of their adopted public policies over time. We examine 55 instances of adopted public policies from 2007 through the first half of 2019

from four major policymaking venues relevant to oil and gas development in Colorado, USA. To extract and analyze the written composition of these public policies, we adapt the original institutional grammar approach (Crawford and Ostrom, 1995) and its more recent rendition in the Institutional Grammar Tool (Siddiki et al., 2019). To guide our analysis, we answer the following two questions:

(1) *How do public policies contribute to the frequency and magnitude of the evolution of a polycentric governance system through major policymaking venues?*
(2) *What patterns of interdependencies between major policymaking venues can we observe through public policies in a polycentric governance system?*

Theoretical Approach to Measuring Polycentricity

This article examines a polycentric governance system that deals with a public policy phenomenon, rather than at the scale of the overall structure of a government.[1] All polycentric governance systems involve policymaking venues that function as the "decision-making units" (Ostrom et al., 1961). The policymaking venues denote a type of government organization with the capacity to adopt formal public policies, such as laws, regulations, and executive orders.

The organizations that produce public policies can function both as venues, and as targeted actors. When an organization is in the position of adopting public policies, we refer to them as venues. When an organization is in a position of being targeted by public policies (e.g., where policies require/forbid/recommend particular actions by these organizations), we refer to them as actors. For example, we study four policymaking venues that adopt public policies relevant to oil and gas development in Colorado. These venues include the Governor's office, Colorado's General Assembly, the Colorado Department of Public Health and Environment (CDPHE), and the Colorado Oil and Gas Conservation Commission (COGCC). We explore these four policymaking venues both in the role they play in adopting public policies related to oil and gas development in Colorado and as targeted actors in those same public policies.

In polycentric governance systems, the interdependencies of the policymaking venues can be observed in a number of ways. For example, interdependencies might involve behavioral relations between policymaking venues, such as cooperation, conflict, or competition in designing public policies (Ostrom et al., 1961). When the focus is on behavior, researchers have provided descriptions and explanations of the ways in which actors pressure multiple policymaking venues to adopt public policies. These studies then measure interdependence of policymaking venues circuitously based on the actors involved in them (Lubell 2013; Berardo et al., 2015; García and Bodin, 2019; Fischer and Maag, 2019).

Interdependencies can also be measured via public policies adopted by these policymaking venues that both shape and are shaped by these behavioral intentions (Heikkila and Weible, 2018). Interdependencies of policymaking venues can be direct (e.g., when the policies of one policymaking venue target another policymaking venue) or indirect (e.g., when policies of two different policymaking venues target a scenario involving the same actors or issues). For example, in this study of oil and gas development, public policies might address the oil and gas industry by requiring them to share information about negative externalities, such as air pollution. We measure interdependencies when more than one policymaking venue adopts the public policies targeting aspects of such a scenario. We provide more details of this approach in the methods section.

We do not expect complete overlap of the policymaking venues; such an arrangement would be functionally redundant and, in practice, an example of a monocentric governance structure. Nor do we expect the policymaking venues to be completely independent given that, by definition, we are interested in how they shape (and are shaped by) the same policy-related phenomenon. Our purpose instead is to portray the ill-defined area between independence and interdependence among the policymaking venues, which characterizes polycentric systems in general —not only in our specific case study.

Thus far, we have described polycentricity statically. However, we know polycentric governance systems continuously evolve over time. One of the means by which governance systems evolve is through changes in the public policies they adopt. Governance systems regularly adopt public policies in response to problems, shifts in attention and learning about the environment, and pressure from coalitions of interests

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[1] Our focus can be described as a study of a "policy subsystem" set within a broader overarching political or "macro system" of government (Redford, 1969). We maintain the more generic term of a polycentric governance system for simplicity. However, the distinction is important in lesson drawing. As described in the conclusion, we generalize our results to the study of policy subsystems rather than macro systems.

(Weible et al., 2019; Jones and Baumgartner, 2005). With these adoptions, the policymaking venues shape and reshape the structure of any governance system. Adopted public policies modify such structure in a number of ways including by modifying their targeted actors, issues, rules, or deonitcs (i.e., imperatives). The question then becomes not whether any polycentric governance system evolves over time but rather the nature of its changes and evolution, particularly the frequency and magnitude of the changes. Frequency means how often the policymaking venues adopt public policies that add to the structure of a polycentric governance system. This might happen, for example, consistently every year or more sporadically. The magnitude of change in the composition of public policies is difficult to operationalize, but it could be coarsely approximated by analyzing the textual composition of the polices, from simply counting words to more finely examining the type of changes the policies contain, such as changes in the targeted actors, issues, rules, or deontics.

In all, this study seeks to characterize the structure and evolution of a polycentric governance system by observing the extent of overlap of the policymaking venues and the magnitude and frequency in which these policymaking venues adopt public policies that alter its structure.

Context Overview

The federal government has a limited role in governing oil and gas development in the U.S. outside of federal lands, and state governments have primary authority over governance decisions, such as whether, where and how oil and gas production can be developed (Warner and Shapiro, 2013). These decisions typically arise through state legislatures and different regulatory agencies. States impose various taxes and fees on oil and gas development and create the administrative infrastructure for implementing, monitoring, and enforcing rules targeting this activity. Additionally, state governors have taken some responsibility for decisions over oil and gas development, mostly through executive orders and administrative directives. Local governments, courts, advisory bodies, and some regional authorities may also affect oil and gas development through decisions of their own.

Colorado is representative of the broader landscape of U.S. states in its complex governance system for oil and gas development. The Oil and Gas Conservation Act (CRS §§ 34-60-101 et seq.) establishes that the Colorado Oil and Gas Conservation Commission (COGCC) has primary responsibility in the state to regulate oil and gas and to protect public health, safety, and the environment (§ 34-60-106(2)(d)). The Colorado Department of Public Health and Environment (CDPHE), through its Air and Water Quality Control Commissions, also plays a role in regulating oil and gas, as established under the Air Pollution and Prevention Control Act (CRS §§ 25-7-100 et seq.) and Water Quality Control Act (CRS §§ 25-8-100 et seq.). Local governments in Colorado historically have had more limited authority in governing oil and gas through land-use planning and voluntary agreements with oil and gas operators, although the extent of their authority has been an ongoing source of political debate in Colorado. Concerns over the impacts of oil and gas on local communities, especially in urban areas with rapid uptick in oil and gas development (using hydraulic fracturing and horizontal drilling), increased significantly starting around 2008.

Policymaking venues have responded to the debates and concerns over unconventional oil and gas development in Colorado. The General Assembly in Colorado first revised the Oil and Gas Conservation Act in 2007, requiring new protections for the environment, which led the COGCC to begin comprehensive rulemaking processes. Between 2008 and 2019, the COGCC passed 18 different rules – some new, others modifying existing rules – to address issues such as well spacing, water quality monitoring, operations in floodplains, spill reporting, enforcement, and complaint procedures. The Colorado Air Quality Control Commission under CDPHE went through six rulemaking processes that targeted the oil and gas sector. For example, in 2014 the commission required new technology to mitigate levels of methane and volatile organic compounds (VOCs) leaking from well operations. The Governor of Colorado has influenced policy by passing executive orders directed at the issue of local government advice and consent and the COGCC's penalties for rule violation. The General Assembly has also been active during this 13-year period, passing legislation on issues such as state severance taxes and new directives for the regulatory agencies to address particular policy issues. In 2019, the Colorado General Assembly amended the Oil and Gas Conservation Act again, requiring the COGCC to pass several new regulations on oil and gas, shifting the mission of the COGCC to emphasize protection of public health and the environment, and expanding local government authority to regulate oil and gas production. We elaborate further on this issue in the results section. This fragmented policy landscape that deals with oil and gas production is not unique to Colorado. Across the U.S., oil and gas development is often shaped by a complex tapestry of regulatory actions that spill across the turf of multiple state- and local-level agencies.

Methods

We conducted a semi-automated text analysis to code 55 policies relating to oil and gas development and regulation adopted between 2007 and 2019.[2] We focused on policies from four key policymaking venues: the COGCC, the Air Quality Control Commission under CDPHE, Colorado's General Assembly, and the Governor.[3] We started with 2007 because that year marked the beginning of a growth period in unconventional oil and gas development in the state and because, in the same year, the Colorado General Assembly passed a bill that required the COGCC to undertake major regulatory changes to its practices and procedures. Using the coded data, we portray the interdependence of these four policymaking venues through the written composition of their adopted public policies over a 13-year span.

We draw on conceptualizations from both the original institutional grammar (Crawford and Ostrom, 1995) and its adaptation in the Institutional Grammar Tool (Siddiki et al., 2019) to extract textual data from Colorado's oil and gas policies. The original institutional grammar and the Institutional Grammar Tool help characterize the written composition of public policies through their syntactic categories. Over time, scholars developed and refined the syntactic categories used within the Institutional Grammar Tool to improve the reliability of text extraction from public policies (Basurto et al., 2010; Siddiki et al., 2011; Siddiki et al., 2019).

Despite these advances, challenges remain in scaling up these approaches from a single public policy to a large number of public policies, which this study addresses. One challenge is that the traditional method of textual extraction via hand coding is labor-intensive and time-intensive. We address this problem by building upon a semi-automated approach for text extraction employed by Heikkila and Weible (2018). This approach relies on a pre-identified "thesaurus" (sometimes referred to as a dictionary) that is used for automating the extraction and categorization of words that are indicative of institutional grammar categories from the policy texts, as we describe in more detail below.[4] We started with a thesaurus created by Heikkila and Weible (2018) for analyzing 11 of Colorado's regulations.[5] We expanded the original thesaurus by manually reviewing each of the new policies not included in the previous thesaurus, refining concept categories, and establishing inter-coder agreement on individual words within each category.[6]

Another challenge with upscaling syntactic concepts from both the original institutional grammar and the Institutional Grammar Tool is how to validly analyze public policies at scales beyond the sentence (technically the "institutional statement"). That is, how do the grammatical parts of individual sentences aid in analyzing hundreds to thousands of sentences? For example, in analyzing a handful of sentences, we could analyze the text and draw meaning in who or what fills the subject or direct object of a sentence. In analyzing hundreds to thousands of sentences, however, understanding who or what fills these grammatical positions can be prone to faulty interpretations. To address this second problem, we treat the public policy—rather than the sentences—as the unit of observation, and adapt the syntactic categorizations accordingly. In particular, we adapt three syntactic concepts in the "attribute", "aim", and "deontic" from Crawford and Ostrom (1995) and the "object" from Siddiki et al. (2011).

Table 1 summarizes our approach and provides definitions of the adapted syntactic concepts. The first column lists the conceptual definitions as adapted from Crawford and Ostrom (1995) and Siddiki et al. (2011). For example, Crawford and Ostrom (1995) define the "attribute" as to whom the sentence (i.e., the

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[2] The methods in this paper mirror the methods used in a study of oil and gas governance in California (Heikkila et al., under review), which also extends semi-automated methods employed by Heikkila and Weible (2018).

[3] We do not analyze all potential policies that may affect oil and gas development in Colorado, as some laws and regulations passed before 2007 pertain to oil and gas and were not changed during this time period. Some that are not included, for example, are storage tanks rules under the state Department of Labor and Employment. We also do not analyze court decisions or local government policies. The total number of policies passed before 2007 or in these other policymaking venues are unknown. We analyze all public policies from these four venues over this time period. These venues were chosen because they are the major ones that govern this issue in Colorado. All public policies analyzed in this paper are available upon request to the contact author.

[4] More detailed coding procedures are available from the authors, with step-by-step instructions. For instance, prior to running Automap, all policy texts had to be pre-processed to remove punctuation, headers, footers, and symbols. We also standardized some words across regulations to ensure the automated analysis would differentiate some key words. For example, "commission" might be associated with COGCC in one regulation or CDPHE in another regulation. In addition, we removed sections of policies that were not related to oil and gas development, along with background and purpose statements in regulations.

[5] The original thesaurus was subjected to an inter-coder reliability test to ascertain correct assignment of words from the regulations to word categories. Two coders, who were not the authors, assessed a total random sample of 42% of the words and their categorization in the thesaurus and found 86% were correctly allocated.

[6] Some words were removed in the inter-coder agreement process for inconsistent or ambiguous usage (e.g., words like "permit"). Overall, the thesaurus expanded from 370 to 790 entries.

Table 1: Text- and high-level concepts for 55 public policies in Colorado Oil and Gas governance.

Institutional grammar concept definitions[1]	Number of text-level concepts in the thesaurus	Number of high-level concepts in the thesaurus	Frequency of extracted word(s)
Attribute: The "who" targeted by the public policies	233 attributes	54 actors	8843 actors
Object: The "what" targeted by the public policies	289 objects	8 issues	20767 issues
Aim: The "actions" stipulated by the public policies	248 aims	8 rules	31178 rules
Deontics: The "imperatives" specified by the public policies	20 deontics	3 deontics	11501 deontics
Totals	**790 text-level classifications**	**73 high-level classifications**	**72,289 extractions of words**

[1] The "Attribute", "Aim", and "Deontics" concepts are adapted from Crawford and Ostrom's (1995); the "Objects" concept is adapted from Siddiki et al. (2011). See Appendix for further descriptions.

"institutional statement") applies. We adapt the attribute operationalization to refer to whom the public policy applies, which basically refers to any actor written into the public policy.

The second column in **Table 1** lists the number of words in the thesaurus per conceptual category. For example, the thesaurus had 233 distinct attributes across the 55 public policies. The third column lists the "high-level concepts in the thesaurus," which combines the text-level concepts into more general categorizations. In this study, we collapsed the 233 attributes into 54 actor categories. For example, one of the 54 actor categories involves the high-level concept of "communities" that comprises eight distinct words from the text-level concept in the thesaurus (e.g., words such as "resident", "general public", "community", etc.). See the Appendix for the list of high-level concepts in the thesaurus. As described in the Appendix, we further simplified the actor classifications in **Table 1** from 54 to 11 for the sake of presentation.

Once all the text-level and high-level concepts were created, we used the software Automap to automate the extraction of text in the thesaurus and identify the frequency of words that fit into each of the text-level and high-level categories (Carley and Diesner, 2005). For example, there were 11,501 deontics mentioned across the 55 public policies. These deontics fall into three high-level conceptual categories of "must", "may", and "should," which are drawn from 20 distinct text-level concepts for deontics in the thesaurus.

Findings

Our first research question asks: *How do public policies contribute to the frequency and magnitude of the evolution of a polycentric governance system through major policymaking venues?*
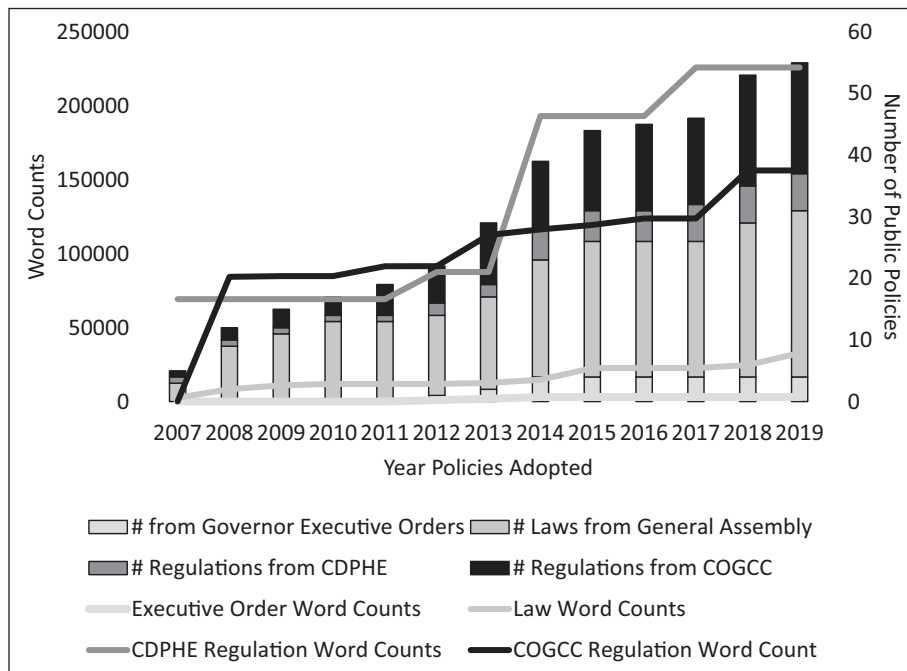
Figure 1 shows the cumulative distribution of policies adopted and their aggregate word count over time. We distinguish between the four policymaking venues by different shades from light gray (the Governor's executive orders) to black (COGCC's regulations).

The number and word count of the public policies adopted in Colorado vary over time and by policymaking venue. Of the 55 policies adopted between 2007 and 2019, the most change, in terms of number of policies, came in 2014 (ten new policies) and in 2008, 2013, and 2018 (with seven new policies). The policymaking venues adopted the fewest policies in 2016 and 2017 (one each) and, for other years, they adopted no public policies.

The Colorado General Assembly penned 27 of the 55 policies with six of those in 2008, and between two to four in other active years. No oil-and-gas-related policies were adopted by the legislature in 2011, 2012, 2016 or 2017.[7] Regarding the total number of policies passed by different regulatory policymaking venues through the years, the COGCC produced 18 of the policies, with 2013 and 2018 being the most active years (four each year). Six policies were passed through the CDPHE, with half of those coming out in 2014. The Governor's office passed four executive orders between 2012 and 2014.

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[7] There was a split Colorado legislature in the following years: 2011–2012, 2015–2018. In other years included in this study, both the Colorado House and Senate had Democratic majorities.

Figure 1: Cumulative Distribution of Word Counts and Policies per Year by Policymaking Venues for Colorado
Oil and Gas Governance System (2007–2019).

The figure shows that the word count generally correlates with the number of policies in a given year.
However, we see a noticeable variation in some years. For example, in 2017, one policy has a long word
count. In other years such as 2010, two policies have very small word counts. Additionally, the regulations
adopted by CDPHE tend to have higher word counts than the regulations adopted by COGCC. The General
Assembly and the Governor tend to adopt policies with low word counts.

The year 2014 appears to be a major year for adopting public policies. However, interpreting the impact
of such changes requires contextual insights. If we were to assume that word counts and number of policies
represent the best indicator of change, we might downplay the importance of the executive orders in 2014.
The Governor's two executive orders in 2014 established the Colorado Oil and Gas Task Force. Although the
two executive orders that created that Task Force had just over 1,200 words combined, they had an important
impact on the governance system. The Task Force had representatives from local government, oil and gas
industry, and environmental groups who discussed some of the deep-seated conflicts around the authority
of local government to govern oil and gas issues and make recommendations to the General Assembly
and COGCC. The result of this process was a regulatory change in 2016 by the COGCC to implement the
Task Force recommendations. The rule change in 2016 imposed new requirements on drilling operations in
urban areas and processes for notifying and engaging with local governments on siting decisions.

Similarly, the most significant change to Colorado oil and gas policy over the last decade arose in 2019
with the passage of Senate Bill 181, which was also small in word count. Senate Bill 181 changed both the
mission and structure of the state's main oil and gas regulatory policymaking venue (the COGCC), granted
new authority to local governments to regulate oil and gas, and changed rules regarding forced pooling of
mineral interests,[8] among other things. This required immediate changes to permitting processes for oil and
gas and may lead to up to 20 new regulations on oil and gas development in 2020 and beyond.

Figure 2 presents four cumulative distribution graphs of the total number of actors, issues, rules, and
deontics written into the 55 public policies by policymaking venues. The COGCC, for example, targets
more actors than other policymaking venues, followed by CDPHE, the General Assembly, and the Governor.
Compared to other policymaking venues, CDPHE targets more rules in total frequency of its public policies.
At different points in the time period under study, the COGCC and CDPHE alternately target the highest
number of issues and deontics relative to other venues. The Governor and the General Assembly adopt
public policies with relatively few actors, issues, rules, and deontics over time. Similar to **Figure 1**, we see
jumps in the number of actors, issues, rules, and deontics in 2014, along with 2007 and 2008.

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[8] Forced pooling laws allow companies to extract oil and gas from a single connected source ("pool") when some portion of the
landowners in the area consent.
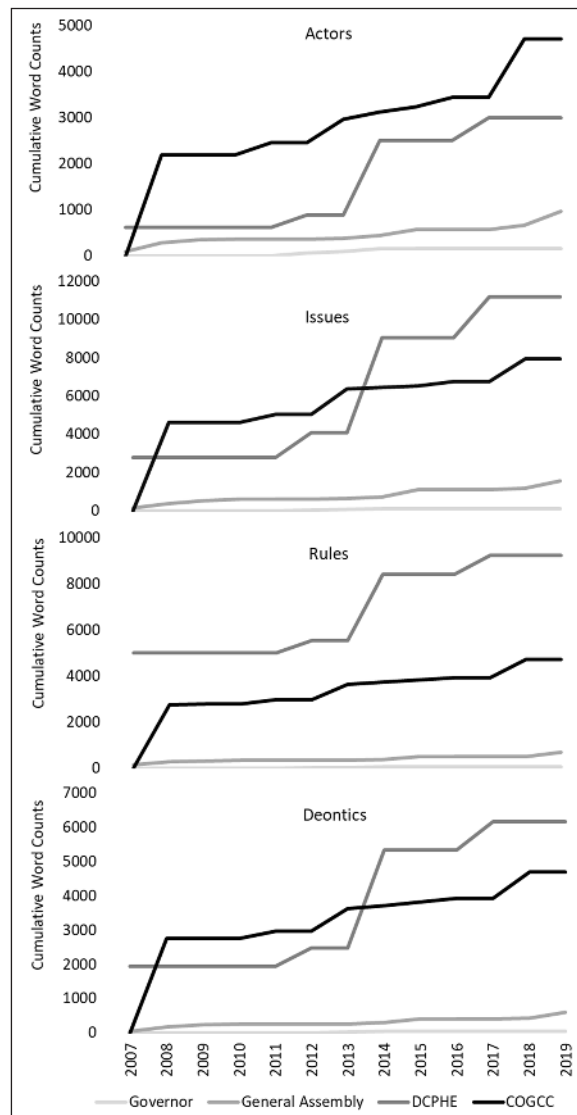
Figure 2: Cumulative Frequencies in Rules, Issues, Deontics, and Actors by Policymaking Venues.

The public policies adopted in **Figure 1** and their more detailed compositions in **Figure 2** represent the accumulating totality of the written modifications for this governance system from its four major policymaking venues. These modifications change the constellation of actors, issues, rules, or deontics that comprise the structure of this governance system, as some public policies replace or amend existing public policies, while others add something entirely new. The cumulative view of such changes provides an image of how these changes collectively add to the responsibilities within the governance system.

In summary, the public policies, as adopted by the four policymaking venues, continuously modify the structure of this polycentric governance system over time. Every year featured at least one public policy adoption. Some policymaking venues were more active than others. The COGCC and the General Assembly adopted the most public policies over time but the two regulatory agencies COGCC and CDPHE adopted public policies with the most word counts. The different policymaking venues contributed in different frequencies for actors, issues, rules, and deontics.

Our second research questions asks: *What patterns of interdependencies between major policymaking venues can we observe through public policies in a polycentric governance system?* To answer this question, we explore the overlap in targeted actors, issues, rules, and deontics as written in the public policies by the policymaking venues. **Figure 3** provides a heat map with black indicating a high frequency of actors, issues, rules, and deontics in the public policies adopted by a particular policymaking venue, whereas white indicates a low frequency.[9]

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[9] For this question, we weighted the frequencies of the number of mentioned actors, issues, rules, and deontics by the total number of words in the respected public policies.
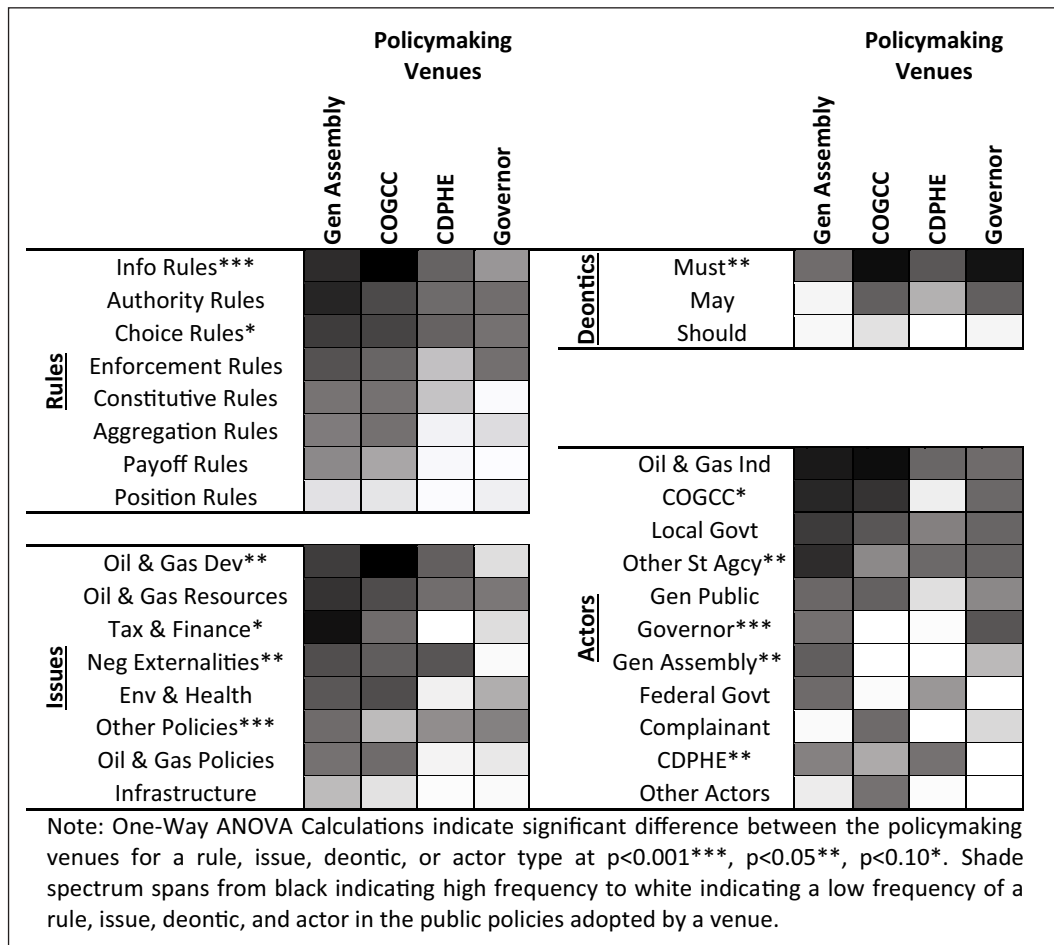
Figure 3: Policymaking Venues Overlapping via Rules, Issues, Deontics, and Actors.

We measure the significant differences between the policymaking venues by One-Way ANOVA calculations. A significant difference (indicated by the asterisks in **Figure 3**) suggests that at least one of the policymaking venues is statistically distinct from the rest. A lack of significance would indicate that the policymaking venues are indistinguishable by either targeting the same actors, issues, rules or deontics at similar frequencies.

In interpreting **Figure 3**, the actors and issues represent similarly targeted animate (in the case of actors) and inanimate (in the case of issues) entities by the policymaking venues. These overlapping actors and issues suggest patterns of interdependencies that are tangible – as they are the "who" and "what" of public policy. The rules and deontics target how those public policies are structured via the stipulated actions (in the rules) and level of imperatives (in the deontics). This form of overlap is related to "how" actors can operate and the stringency imposed on those actions, as written in the public policies. While we separate the actors, issues, rules, and deontics in **Figure 3** to understand their relative frequencies with each of the policymaking venues, in practice they entwine in the structure of this polycentric governance system.

For the actors, the policymaking venues are most distinct when the policies they pass target policymaking venues. Significant differences between the policymaking venues occur for the following targeted actors: COGCC, Other State Agencies, the Governor, the General Assembly, and CDPHE. This reflects the vertical interdependencies of this governance system and the distinct authorities and niches of the policymaking venues. For example, CDPHE rarely targets COGCC in its public policies because of its niche of focusing on regulating air pollution from oil and gas development. However, COGCC, being the more generalized regulatory agency for oil and gas development in Colorado, targets CDPHE in its regulations. Additionally, these two regulatory agencies do not target the Governor in their public policies.

There are also indications of horizontal interdependencies in this governance system. For example, the four policymaking venues are indistinguishable in terms of the non-government entities including oil and gas industry, complainant, and other actors identified in their public policies. They also do not differ in targeting local governments (which are targeted equally across the policymaking venues) and the federal government (which shows some variation but not enough for statistical significance).

Horizontal interdependencies are also evident with the issues. The issues captured within the policies produced by the four policymaking venues reflect their overlapping niches in this governance system. The policymaking venues are statistically indistinguishable in their focus on oil and gas resources, environment and health, other oil and gas policies, and infrastructure. Of these, oil and gas resources are the most common issue they all address. The four policymaking venues differ in the extent they deal with oil and gas development (not a major focus by the Governor), tax and finance (a major focus by the General Assembly but not by CDPHE), negative externalities (not a major focus of the Governor), and other public policies (low frequency for COGCC). The venues, overall, show similarities in some issues but particular niches in others.

When observing the rules and deontics encompassed in public policies, the four policymaking venues appear most uniform. All tend to use diverse types of rules (shading consistently goes from dark to light for all four policymaking venues). The most common rules are information, authority, choice and enforcement rules, with the least common rules being position and payoff rules. The venues vary little in their frequency of rule use with statistically significant difference in information and choice rules (the Governor uses them less than the other policymaking venues). For the deontics, all use more "musts" than "mays" and "shoulds" with COGCC and the Governor using "musts" more than the other venues. The patterns in the use of rules and deontics might reflect the regulatory purpose of this governance system as they are indicative of policies that require actions that "must" be done, and include rules indicative of who has authority for collecting information (e.g., potentially for monitoring) and patterns of rules that emphasize enforcement.

In all, we see different patterns of interdependencies across the venues. When it comes to vertical interdependencies between policymaking venues, we see more differences between venues in how their policies target other venues. On the other hand, when it comes to horizontal interdependencies, or how venues target non-governmental entities, we see more similarities across venues. They also show patterns of horizontal interdependencies across venues in their focus on issues but not without differences in foci. The policymaking venues tend to use rules and deontics in a similar way with some using them in higher frequencies than others.

Conclusion

Our analysis was guided by two questions: *How do public policies contribute to the frequency and magnitude of the evolution of a polycentric governance system through major policymaking venues?* And, *what patterns of interdependencies between major policymaking venues can we observe through public policies in a polycentric governance system?* In answering these questions, we address an enduring challenge that hinders the advancement of knowledge about polycentric governance systems: systematic measurement and description of its structural interdependencies and evolution. In the context of oil and gas development in Colorado, our approach centers on four policymaking venues and 55 public policies adopted from 2007 through 2019. We adapt the institutional grammar (Crawford and Ostrom, 1995; Siddiki et al., 2019) to extract actors, issues, rules, and deontics from the public policies to portray the evolution of a polycentric governance system and the interdependencies of the policymaking venues.

For the first question, the results show how four policymaking venues adopt public policies that change the structure in this governance system over time. Every year between 2007 and 2019, these policymaking venues adopt changes with most years showing steady but smaller change and a few years showing larger change. While we can understand these changes in the number of public policies and word count, a closer examination reveals that the policymaking venues target actors, issues, rules, and deontics at different frequencies in any given year and variably over time. The result is a depiction of evolving structure that changes through ongoing adoptions of public policies that affect the governance of oil and gas development in Colorado.

For the second question, we portray the structure of polycentricity by the varied interdependencies of four policymaking venues through the public policies they adopt. The interdependencies of the policymaking venues are observed in the degree of overlap in shared focus on the actors, issues, rules, and deontics. The results highlight that the policymaking venues show vertical interdependencies when they target other state-level policymaking venues. The policymaking venues show horizontal interdependencies in overlapping niches when they target non-governmental entities, local and federal governments, and issues. The policymaking venues also share a similar priority for certain types of rules (e.g., information, authority, and choice) and certain deontics (e.g., musts). In all, the interdependencies we observe likely reflect the hierarchical structure of federalism in the U.S. and the overall complexity of oil and gas development as somewhat fragmented and governed by specialized policymaking venues. This could be further explored in future research on other policy areas or contrasted with other government styles using the same methodology.

Methodologically, this article contributes to ongoing efforts to analyze institutions as written in public policies (Crawford and Ostrom, 1995; Siddiki et al., 2019). Much of this prior work has been conducted via hand coding, which limited the number of policies analyzed and kept these studies within short time spans. Through a semi-automated approach, we were able to upscale the analyses to incorporate dozens of policies over an extended period. To make this happen, we focused on treating the entire public policy as the unit of observation and adapted the original conceptual definitions of the institutional grammar (Crawford and Ostrom, 1995) and of the Institutional Grammar Tool (Siddiki et al., 2019). We then gained the capacity to specify the unique signature of each policymaking venue on this governance system through the aggregation of their adopted public policies. While our use of public policies as the unit of observation creates limitations, it also reveals new ways for examining policymaking venues and public policies at larger scales and, eventually, finding descriptive and explanatory patterns comparatively and longitudinally.

Crucially, this article contributes to the literature by offering a complementary approach for portraying polycentricity that extends prior research using similar methods (Heikkila and Weible, 2018) by encompassing a more complete picture of the governance system. Notable efforts to measure interdependencies often do so by reported behaviors in, for example, surveys of a sample of actors or through various behavioral indicators gathered through case study methods (Lubell, 2013; Morrison, 2017). In this literature, for example, researchers might measure the interdependencies based on the reported behaviors of actors who participate in different policymaking venues and then link those policymaking venues together based on the number of actors these venues share (see Lubell 2013 for an example). The approach in this study does not focus on the inputs (e.g., pressure and partitions by actors in the policymaking venues) but on the outputs (e.g., the policies adopted by these policymaking venues) to portray a polycentric governance system. Obviously, tradeoffs are evident in both approaches. The strength of the current approach involves its potential to inform the evolution of these systems over time and their policy-based structure across different contexts. Among the next steps is the combination of these different methods for measuring polycentricity and their application across time and space.

The importance of this study lies in its future contribution to better understanding the linkages between polycentricity and performance of polycentric governance systems. However, this study raises a number of additional challenges in understanding such linkages. For example, this study shows that polycentric governance systems evolve as adopted public policies modify the different combinations of existing and sometimes new actors, issues, rules, and deontics. If we were to assess outcomes of any polycentric governance system, what point of its evolution would we mark for evaluation? In other words, polycentric governance systems are better imagined as ongoing processes of change and interactions with their environment rather than as static phenomena detached from their environment. This requires new ways to approach performance both theoretically and methodologically.

In conclusion, this study addresses some of the fundamental challenges in advancing knowledge about polycentric governance systems by focusing on its measurement and how it evolves over time. By focusing on cumulative effects of public policies, we provide a systematic and replicable approach for analyzing the interdependence of policymaking venues over time. This approach provides a means for broadening the type of questions asked about polycentricity and including more comparisons across space and time. The breadth of our approach allows for the spawning of new insights that may eventually elicit the linkages between polycentricity and performance, leading to fruitful recommendations on improving governance.

Appendix

Attribute & Actor Categories. The attributes represent "to who" the public policies apply with the thesaurus including 233 distinct words. We then manually classified these 233 attribute categories into 54 more generalized distinct actor categories. For the analysis, these actors were further organized into 11 categories: 1) CDPHE (which includes separate divisions within the agency such as air and water); 2) COGCC; 3) other state agencies; 4) the Governor; 5) the General Assembly; 6) actors associated with formal regulatory complaints, including "complainants", "respondents", and "intervenors"; 8) the general public or community actors; 9) oil and gas industry; 10) local governments; 11) federal governments.

Object & Issue Categories. We define objects as the topical targets of the rules of a policy. Based on reviewing all 55 policies, we identified 288 object terms for the thesaurus, which were clustered into eight issue categories.

1. *Oil and Gas Development* includes words associated with processes or technology involved in producing oil or gas. This includes anything on the well site, drilling technology, tanks, collection and distribution systems for oil and gas, etc.
2. *Infrastructure* refers to any infrastructure that is tangential or separate from the oil and gas processes (e.g., housing, roadways, buildings, recreation areas).
3. *Oil and Gas Policies or Strategies* include any policies or formal strategies that are related to how the oil and gas development process occurs, such as well permits, or policies mitigating the effects of oil and gas development (e.g., leak detection, setbacks, best management plans).
4. *Other Policies* are the laws and rules that are referenced in the policies that are not directly or primarily related to oil and gas (e.g., the Clean Water Act or eminent domain).
5. *Tax/Finance* includes all words referencing severance taxes, public finance, funds, money, etc.
6. *Oil and Gas Resources* words identify any resource extractable from the natural environment, or that describe the geophysical properties of these resources, such as oil, gas, coal, ores, minerals, vein, fuel, ledge, and petroleum.
7. *Environment or Health* words refer to human health and safety, the environment, wildlife, and resources independent of oil and gas (e.g., groundwater, streams, floodplains) that are often affected by oil and gas development.
8. *Negative Externalities* are those words that directly imply an adverse impact from oil and gas development, such as produced water, waste, surface disturbances, seismicity, etc.

Aim & Rule Categories. The "aim" represents the "actions" stipulated in the public policies, which corresponds with verbs in the public policy. The thesaurus lists 248 distinct aims, which were then classified into 8 rule types. The rule categories adapt those found in the Institutional Analysis and Development Framework's rule typology (Ostrom, 2005).

1. *Aggregation rules:* Words that indicate collective decision-making comprise this category. This includes words like "discuss," "consult," "negotiate," and "settle."
2. *Authority rules:* These words grant authority to an actor and are indicated by words such as "allow," "approve," "mandate," "regulate," and "select."
3. *Constitutive rules:* This category includes words that define phenomena, including "declare," "define," "comprise," and "deem."
4. *Choice rules:* This category of words refers to actions and decisions about oil and gas procedures, such as "build," "flush," "install," "load," "drill," and "operate." It also includes words that blur rule categories, including "employ," "maintain," and "serve." This serves as a catchall category, as defined in the rule typology (Ostrom, 2005).
5. *Enforcement rules:* This category encompasses words that refer to enforcing regulations or imposing penalties for failures to meet regulatory expectations (e.g., "enforce," "compliance," "fines," "penalty," "prohibit").
6. *Information rules:* These words indicate collecting, giving, disclosing, documenting, or receiving information (e.g., "document" or "receive"). This category includes words about monitoring behavior, inspecting, and reporting (e.g., "monitor" or "report") and excludes words related to enforcement.
7. *Payoff rules:* These words indicate requirements for one actor to provide funds to or receive funds from another actor (e.g., "pay," "distribute," "compensate," and "deposit").
8. *Position rules:* These words indicate how actors fills positions or the structure of those positions (e.g., "appoint", "compose", or "serve").

Deontic Categories: Deontics are the imperatives that provide force or discretion in public policies. The thesaurus listed 20 text-level concepts (e.g., "ought to", "need to", "shall", "will be") that were then categorized into 3 high-level concepts ("must", "may", and "should").

Competing Interests
The authors have no competing interests to declare.

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