RESEARCH ARTICLE

A spatially explicit ontology for the institutional analysis of social-ecological systems

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Abstract: Dynamics within complex social-ecological systems (SES) are the product of a diverse array of socio-economic and biophysical processes. The spatial structure of these systems often influences the management of resources (e.g. forests, water, fish) including the institutional rules that are developed governing how these systems can be used. Prior work has developed frameworks to describe SESs to address what institutional contexts make SESs resilient or sustainable, but without articulating the spatial relationships inherent in these systems. The objective of this paper is to develop an ontology designed to describe the actors, resources and relationships within an SES, with an emphasis on the spatial relationships inherent in human-environment interactions. This ontology can be used to explore what spatial structures contribute to the resilience or sustainability of SESs. Many elements of SESs have explicitly spatial characteristics that in part affect the dynamics within those systems such as the proximity of actors to a resource, or the size of land holdings. The ontology presented here emphasizes the actors and resources in a system as well as the spatial characteristics and relationships that relate to the institutional factors affecting system dynamics. A series of three distinct case studies are used to demonstrate how this ontological framework can be applied to specific SESs. While the presentation here focuses on community level dynamics, the general framework presented here is broadly applicable to a wider array of analytical scales from local to regional level dynamics.

Keywords: Ontology; Social-ecological systems; Institutions

1. Introduction

Common-pool resources (CPR) such as trees in a community forest, water in irrigation systems, and fish or scallops in fisheries are embedded in social-ecological systems and their importance for natural resources management is well established in the literature (Dietz, Dolsak et al. 2002). CPRs have many spatially explicit characteristics, as do the households, communities and societies that manage them. Accordingly, the institutions (i.e. resource management regimes) that people develop in an effort to manage CPRs effectively vary with social and ecological spatial properties. For example, the institutions that affect the management of a 1 ha community forest develop in a dramatically different context than that for a trans-national park that is 100,000 ha in size. Some resources are relatively immobile (timber in community forests) while others are highly mobile (e.g. water in irrigation systems, wildlife in forests) (Schlager, Blomquist et al. 1994; Altrichter and Basurto 2008). Some park boundaries are well defined and recognized while others are imprecise and vague. A large, heterogeneous community may develop a different institutional solution for pasture management than a small cluster of households that have tight familial linkages (Varughese and Ostrom 2001). These diverse relationships have important implications for the management of CPRs and the resource management regimes that develop in different social-ecological conditions. Given the complexity of social-ecological systems in which CPRs are embedded, it is difficult to conduct synthetic or cross-site analysis without a framework to characterize these systems. Thus a major challenge in developing such a framework is the identification of components to describe the spatial relationships inherent in these social-ecological systems.

There are a number of case studies that have addressed the influence of spatial characteristics in the institutional analysis of CPRs management (Schlager, Blomquist et al. 1994; Levin and Harvey 1999; Wilson 2002; Turner, Matson et al. 2003; Lansing 2006; Ostrom 2007). But there has not yet been an attempt to organize this type of analysis, and success at drawing conclusions spanning case studies has been elusive. A series of coding efforts of numerous case studies have provided an initial understanding of important conditions that can increase the likelihood of communities managing their CPRs sustainably (Ostrom 1990; Tang 1992; Schlager, Blomquist et al. 1994; Lam 1998; Cox, Arnold et al. in review). However, the emphasis has been on identifying specific institutional arrangements without articulating their spatial context. Spatial structure provides one common language that can facilitate cross-site analysis of SESs and help further explain the functions and performance of these institutional arrangements.

The objective of this research is to develop a spatially explicit ontology that can enable the cross-site analysis of social-ecological systems (SES), including the influence of institutional forces on those systems. We present a spatial framework to describe the intersection between institutions, people and common-pool resources and demonstrate how this framework can be applied to three diverse case studies. While the paper draws examples from a set of three specific CPRs, the framework is broadly applicable to a wide range of social-ecological contexts.

2. Background and foundations

This section provides a brief review of conceptual research on social-ecological systems (SES) and the development of ontologies in spatial contexts. There is a distinct bridge between these two science domains that we address in the development of an ontology for social-ecological systems described later in this paper.

2.1 Social-ecological systems and natural resource management

Research on the dynamics in social-ecological systems (SESs) is quite diverse, although it is characterized by several organizing concepts. These include resilience and robustness, disturbance and perturbation, and complexity. A closely related, and somewhat overlapping, literature has focused on the resolution of collective-action problems in common-pool resource (CPR) settings, by some mix of institutional arrangements, biophysical conditions, and user group properties (Ostrom 1990; Ostrom 2005). In this literature, institutions as rules function to provide incentives that help groups of resource users overcome the divergence between individual and collective interests they face, and collectively manage a natural resource. Berkes et al. (2003) represents an integration of these two approaches, viewing a SES as a combination of institutional arrangements and ecologies, each nested across several scales.

Overcoming collective-action problems is difficult because participants are uncertain about the future actions of others, and have reasons to expect some degree of self-serving behavior on their part (Hardin 1968). Many scholars studying community-based CPR management have focused on the role institutions play in overcoming these difficulties. North (1990) states that institutions arise in order to reduce the uncertainty in social situations by ordering participants' relationships. By reducing uncertainty, trust and norms of reciprocity may be built and sustained, and collective action may become possible. Thus, institutions are an important set of independent variables that affect outcomes in collective-action situations. Institutions are defined by Ostrom

(1986) as “potentially linguistic entities . . . that refer to prescriptions commonly known and used by a set of participants to order repetitive, interdependent relationships” where “prescriptions refer to which actions (or states of the world) are required, prohibited, or permitted.” In SESs an institution may involve the rules that restrict lobster harvesting when populations fall below a certain threshold, or the actors who are allowed to harvest timber in a community forest based on how long they have lived in the community.

Several frameworks have been proposed for studying SESs, including Gunderson and Holling’s (2002) Panarchy concept, Ostrom’s (2007) hierarchical framework, Anderies et al. (2004), Janssen et al.’s network approach (2006), and the robust control framework presented by Anderies et al. (2007). Anderies et al. (2004) defines an SES as four components: (1) A resource, (2) Resource users, (3) Public Infrastructure, and (4) Public infrastructure providers, as well as the possible inputs and outputs for each component. Janssen et al. (2006) define a SES as a network of nodes and links, and focus on analyzing SESs via the statistical properties of their networks, as is common in network analyses. A related body of work has focused on the properties of the social networks of individuals who manage natural resources (Bodin, Crona et al. 2006; Bodin and Crona 2008).

Gunderson and Holling’s work emphasizes the nonlinear temporal dynamics of SESs over time as they proceed through an adaptive cycle. In this adaptive cycle, any complex social or ecological system transitions from a period of growth and accumulating connectedness between its components, through a collapse to a period of renewal and reorganization that leads to further growth, restarting the cycle. The framework recognizes that multiple adaptive cycles may be nested one within another. This necessitates the incorporation of multiple nested spatial scales as slower moving adaptive cycles are associated with larger spatial scales.

Ostrom’s (2007) framework likewise attempts to recognize the hierarchical qualities of complex social-ecological systems, although the focus is analytical rather than spatial or temporal. A tiered framework where components of a SES are in turn decomposable into multiple subcomponents or properties results in an explicitly hierarchical structure. There are six primary components of an SES in this design: (1) A resource system, (2) Resource units, (3) Users, (4) A governance system, (5) Related ecosystems, and (6) External social, economic, and political settings. This framework includes some explicitly spatial properties such as the mobility and spatial/temporal distribution of the resource units, as well as the location of the users and the resource system, but does not articulate the role of spatial relationships in the system.

Finally, Anderies et al. (2007) present a framework defined by the robustness of social-ecological systems. This framework reflects the engineering origins of robustness as “the maintenance of some desired system characteristics despite fluctuations in the behavior of its components parts or its environment” (Carlson and Doyle 2002). This framework represents an SES as a decision-making component and a biophysical component that iteratively send signals to one another, constituting a feedback loop. The signal the decision-maker has is the output from the biophysical component, and the goal is to adopt a decision-making rule that maintains this output at a certain level or within a certain range given the behavior of the biophysical component, along with signal noise and external perturbations. These various frameworks have helped describe the structure of SESs, but have not focused on the spatial relationships that affect the dynamics within these systems.

2.2. Ontologies and applications to social-ecological systems

Ontologies have been suggested as tools to facilitate the accessibility and interoperability of spatial data (Smith and Mark 1998; Kuhn 2001; Agarwal 2005). Ontologies have also been developed to allow information systems to better manage and translate spatial data (Fonseca, Egenhofer et al. 2002; Timpf 2002; Agarwal 2005). Perhaps most importantly, the structure provided by ontologies can be used to create order from complex systems (Agarwal 2005). These attributes are of particular utility given the challenges of characterizing complex systems and the desire to produce effective cross-site analyses of social-ecological systems with generalizable findings (McConnell and Keys 2005). Cross-site analyses require some standardization of data which in part is provided by ontological frameworks that facilitate the translation of data across different sources(Chandrasekaran, Josephson et al. 1999; Fonseca, Egenhofer et al. 2002).

While there have been previous attempts to develop data management systems for ecological data (Baker, Benson et al. 2000; Bowers and Ludascher 2003), there has been less attention given to systems of coupled social-ecological dynamics. Part of the challenge with these efforts is the inherent complexity in social-ecological systems (Anderies, Janssen et al. 2004) and the task of applying theoretical developments in ontologies to specific domains. Domain specific ontologies have been developed to define the categories and relationships in what can be considered complex systems. For example, Kuhn (2001) proposed a framework for modeling by organizing the information in the German Traffic code. Ontologies have also been developed for remote sensing data (Bähr 1998, Fonseca et al. 2002 and Comber et al. 2004, Ahlqvist 2005), land development (Kaza and Hopkins 2007) and environmental planning (Boothby 2004; Pastorello, Medeiros et al. 2005). Such efforts to organize data related to land cover, especially those that incorporate human dynamics, are particularly relevant to applications to SESs given the importance of these two domains to the system dynamics.

Semantic issues related to the vagueness and ambiguity of spatial features have been highlighted as an obstacle in geographic representation (Agarwal 2005) which has implications for the characterization of SESs. One study may find that lakes “near” agricultural areas are at risk of eutrophication without defining the specific value of this distance relationship. Thus it is difficult to disentangle the challenge of producing an ontology for the study of complex systems from the issues related to semantics (Bishr 1998).

A core challenge in the study of social-ecological system is the definition of the dynamics that are responsible for the resilience and stability of the system. A substantial number of domain theories focus specifically on object classes and categorization without addressing dynamics such as events, actions and processes (Kuhn 2001). But it is these types of system dynamics that are of particular importance to the study of complex systems. Activity based ontologies (Câmara, Monteiro et al. 2000; Kuhn 2001) offer a useful model for the development of frameworks designed for dynamic systems, including complex social-ecological systems.

What characteristics should an ontology of SESs have? Agarwal (2005) defines four considerations in the design of geographic ontologies: 1) spatial and temporal concepts, 2) resolution of spatio-temporal integration and the object-field dichotomy, 3) resolution of vagueness and ambiguity in geographic information and 4) resolution of issues in applying higher-order ontology to vague concepts. Each of these considerations is relevant to the development of ontologies for social-ecological systems. Spatial and temporal context have clear implications for the definition of system dynamics, and spatial structure affects the resilience of many social-ecological systems (Nyström and Folke 2001). Data collection methods to characterize land management and decision-making highlight the importance of semantics in defining distance relationships (e.g. distance to markets).

3. Spatially Explicit Ontology of Social-Ecological Systems

The foundation for the ontological structure presented here is defined by the salient components within a social-ecological resource system and the relationships between those components. Many of those relationships are explicitly spatial, including the fundamental challenge of defining the spatial boundaries of a system or what defines a “closed system”. Here we focus on a community scale approach and set of case study examples, although we acknowledge that there are complex social-ecological systems that are not as driven by local-level forces as the examples we describe here. However, in order to describe the spatial relationships within institutional settings we focus on this community scale context, as this is the level at which much of the common-pool resources institutional literature has focused in the past.

The main components of the framework are the *actors*, *resources* and *institutions* (Figure 1) within a SES. This framework is an extension of Ostrom's diagnostic conceptual design (2007) which is defined by users, a resource system, resource units and a governance system. Actors are components of the social-ecological system with some participation in decision-making processes specifically with regards to the management or utilization of resources. For example, a village may have a committee of residents that makes decisions about local property rights that are allocated to specific households. Thus the community committee is an actor in the SES that in part is responsible for the pattern of land management in the community. Households in turn make land management decisions about partitions of the landscape that are allocated to them. So this system would have both a community committee actor as well as a set of household actors. Each individual actor within a specific actor class is referred to as an instance of that class.

The basis for the spatial relationships within a social-ecological system is articulated by the relationships between the core components, i.e. actors, resources, and institutions. There are two main types of relationships in the ontology. First, institutional action-based relationships consist of a management or governance action applied by an individual actor to a specific object of the action. Here we represent these action-based relationships with the following structure:

<Actor+Action+Object>

Actors and objects can take different forms depending of the research question and scope of interest to the researcher. For instance, an actor can take the form of a household making decisions about the management of a parcel of land. This would be represented as <Household+Manages+Parcel>. Examples of management or governance actions include *harvest*, *own*, *sanction*, *monitor* or *enforce*. Once constructed, the action-based structure can be used to identify each actor who affects a particular resource, and the chain of actions that affect a particular resource.

The second type of relationship in the ontology are spatial relationships. These are used to define the spatial structure of the system that affects system function. These spatial relationships are represented as:

<Actor.spatial-relationship.Object>

or

<Resource.spatial-relationship.Object>

where object is usually a resource of interest to the researcher (e.g. scallop, timber or a parcel of land).

Topological rules are used to define these system characteristics which include the following (Egenhoffer and Franzosa 1991):

COVEREDBY
COVERS
EQUAL
CONTAINS
INSIDE
COVERS AND CONTAINS AND EQUAL

COVEREDBY AND INSIDE AND EQUAL
TOUCH
OVERLAPBDYINTERSECT
DISJOINT
TOUCH AND OVERLAPBDYINTERSECT
ANYINTERACT

In addition to these topological rules, system relationships are often described using semantic forms such as NEAR and FAR (Worboys 1992; Grigni, Papadias et al. 1995) in the SES case study literature and we allow the use of these semantic terms here. We then use triples to define key linkages in the system. An <Actor.Relationship.Resource> triple defines the relationship between an actor and a resource, while <Actor_a.Relationship.Actor_b> describes the relationship between two actor classes. For example, one instance of the Household class can be associated with an instance of the FishingGround class via the Near relationship (<Household_x.Near.FishingGround_y>). Spatial relationships can exist with resource class types as well (e.g. <Scallop.Inside.FishingGround>).

As with Kuhn (2001) we consider actions as having an actor and an object of that activity. In implementing this frameowork we code actions that are perceived to be the most salient to the dynamics of the SES. This is clearly a subjective decision made by the researcher who is hopefully familiar with the dynamics driving the SES. Any system has a multitude of dynamics that are of potential relevance to a particular actor instance, but can be considered less significant than overarching dynamics that affect the majority of actors in a system. For example, a household allowed to harvest timber from a community forest may be limited by the amount of labor the household can expend due to seasonal migration for wage labor, health of the household members or the demographic characteristics of the household. But if these household attributes are responsible for only a small deviation from the average timber rate of all households than a decision can be made to exclude these from the implementation of the ontology.

4. Applications of Ontological Framework

To describe how this ontological framework can be implemented, we describe three distinct case studies and demonstrate how the structure and dynamics of these SESs can be defined. We have intentionally selected case studies that include a variety of resource types to emphasize how the ontology can be used to describe the spatial structure of the system within the context of the institutions affecting resource use. The first case study describes an irrigation network in the southwest united states where the common-pool resource is water and the actors manage access to water in the irrigation network. A second case study describes an intentional community (Questenberry 1996) that includes private and communal property with forest as the resource of interest. The last case describes a fishery in the Gulf of Mexico where the harvesting of scallops in a series of distinct fishing grounds is managed by community members.

4.1 Acequias system

The acequias in Taos valley of northern New Mexico are an example of a community-based natural resource management system (Figure 2). They have historically persisted by transporting water to irrigate land in a high desert environment. Such harsh conditions, with low levels of technology, have required sustained collective action on the part of the users in order to assure that each individual is able to grow enough crops and survive in the area. Irrigation systems such as the acequias, where humans continually interact with each other and with land and water resource systems, are excellent examples of social-ecological systems.

While they are relatively decentralized, the acequias do have key actors who have more authority with respect to the resource system and regular members. Each acequia has a mayordomo and a commission (most commonly made up of a president, a secretary, and a treausurer). Is it the mayordomo who is in charge of allocation water within each acequia. When disputes arise between acequias, no one acequia or acequia official has authority over other acequias. Instead, mayordomos and/or commissioners may meet in order to resolve a dispute in times of scarcity in accordance with historic practices. The acequias interact with four different resources: a surface water system, a groundwater system, an irrigation infrastructure (headgates and canals), and a land resource system.

4.1.1. Spatial relationships

The acequias employ several institutional arrangements in order to manage the resources in their resource system. These can be understood better through the spatial relationships that they exhibit. First, the groundwater resource, the land resource, and the acequia members all cluster around the linear surface water resource and irrigation infrastructure that makes the surface water available: <Groundwater.Near.Surfacewater>, <Land.Near.Surfacewater>, <Members.Near.Surfacewater>. Drakos et al. (Drakos, Lazarus et al. 2004) describe a very close connection between surface water and a shallow groundwater system in Taos valley. This is also reflected in qualitative accounts by members that were interviewed, as well in hydrological work conducted on acequias in other parts of New Mexico (Fernald, Baker et al. 2007). The land resource and actors cluster near the surface water resource and partially overlap the groundwater resource because in such an arid environment, land has little or no value without the availability of water subsidies.

Because the private parcels of land are contiguous, and members reside on their private parcels, this creates a potential conflict over water use between acequias along different reaches of a river. Thus, the acequias as a decentralized system have to cope with potential conflicts both within and between acequias. Both these conflicts are part ameliorated by the partial overlap between the land resource and the groundwater research, as both cluster near the surfacewater resource. In times of surface water scarcity, many of the acequias may rely on groundwater seepage as an alternative source of water.

4.1.2. Institutional arrangements

The resolution of conflicts is quite different within acequias than between them. The linear branching property of the surface water resource leads to a nesting of institutional arrangements within acequias. At the lowest level, members privately own parcels of irrigated land as well as the ditch and headgate that most directly feed their parcel: <Member_X+Owns+Parcel_X>, <Member_X+Owns+Headgate_X>, <Member_X+Owns+Ditch_X>. The main canal, the land immediately on each side of it, and the main headgate off the river headgate are common property and are managed mostly by the mayordomo <Acequia_X+Owns+MainCanal_X>, <Acequia_X+Owns+MainHeadgate>.

Within acequias, members tend to indirectly monitor their neighbors' use of water, by noticing when water is unavailable during their period of allocation, caused by a neighbor using water out of turn <Member_X+Monitors+Neighbors>. This practice is enabled by the contiguity between private land parcels, as well as by the use of a rotational system of surface water distribution with each farmer allotted a time in a schedule maintained by the mayordomo. Additionally, the mayordomo actively monitors the use of water for the whole acequia: <Mayordomo_X+Monitors+Acequia_X>.

The institutional arrangements between acequias have been likened to international diplomacy, and there is no obvious property regime that exists for the main river that a group of acequias may each divert from. There are no formal monitoring or sanctioning mechanisms at this level, although in many situations there is a standing agreement between acequias about how to divide the water in times of scarcity. Again, it is likely that in many instances the need for formal arrangements between acequias is lessened by the availability of groundwater, even during droughts (Rodriguez 2007).

4.2. Intentional Communities and Forest Management

An intentional community is "a group of people who have chosen to live together with a common purpose, working cooperatively to create a lifestyle that reflects their shared core values" (Questenberry 1996). These communities design, implement, monitor and enforce a set rules or institutions to manage the forest and its products.

Tulip Poplar in Southern Indiana in the United States is an intentional community development surrounding two man-made lakes. Tulip Poplar includes a series of landscape partitions of both private and common property. Individual lots are privately owned and governed by private property land rights which are restricted by community covenants <TulipPoplar+Owns+PrivateProperty> <TulipPoplarOwners+Own+CommonProperty>. The common areas consist of the two lakes and a sizable forested area within the community boundaries <Community.Contains.Lakes> <Community.Contains.Forest>. These areas are managed by a neighborhood association, of which all landowners and their families are members <Landowners.Inside.NeighborhoodAssociation>. The rules governing the types of authorized uses of the forest and lakes by members of the association are established in the association rules and regulations handbook <ResourceSytem.CoveredBy.RulesAndRegulationsHandbook>.

The neighborhood association owns and manages 197.8 acres of forest dominated by sugar maple and tulip poplar trees which are common species in this region. None of the families living in the community rely upon the forest for daily subsistence activities; however landowners regularly extract a variety of products from the forest such as firewood, morel mushrooms and ginseng (Poteete and Welch 2004). Landowners also derive secondary benefits such aesthetic enjoyment and recreational opportunities.

The forested areas of Tulip Poplar are divided in two categories: private and communal (Donnelly, Ostrom et al. 2004). The six patches of land owned and managed by the community are surrounded by private forests with no boundaries demarking the end of the communal forest <CommunityForest.Within.CommunityBoundary>, <CommunityForest.Adjacent.PrivateForest>. Within the communal forest a portion is managed under a classifed forest and wildlands program established by the Indiana Division of Natural Resources <CommunityForest.Contains. ClassifiedForest >. The program restricts development of the property and requires preparation of a management plan (Nelson 1998). In return, the community receives up to 90 percent break in property taxes.

The community of Tulip Poplar governs their common and private forests by separate sets of user rules. As of 2005, private forest owners need to obtain a permission from the Association to log any tree bigger than six inches in diameter at breast height (DBH). This rule was established after a landowner decided to clear cut his forest increasing the erosion problem already occurring around the lakes. In general, harvesting forest on private property lands is motivated by the need of firewood, to gain access to the lakes, or for home construction. In communal forests, nobody (community members included) is allowed to take any firewood <Firewood.Inside.CommunalForests>. Other products such as morels mushrooms and ginseng are harvested by some residents but are not major contributors to total income. This community does not have serious trespassing problems with outsiders. Hunting is allowed, during the hunting season but firearms are prohibited.

With regards to the spatial structure of the community, the fact that private landowners are in such close proximity to the communally managed forest is a significant characteristic. Also, the fact that parcels are relatively small (size) means that landowners can observe the activities of other landowners relatively easily.

4.3. Seri Indigenous Coastal Fishing Community

The Seri indigenous community stands out among other fishing communities in the Gulf of California, Mexico (Figure 3), for their ability to govern and conserve their fishing resources without collapsing the social-ecological system in which they depend on (Basurto 2005; Basurto and Ostrom 2009). The Seri mostly harvest two species of callo de hacha (CDH): *Atrina tuberculosa* and *Pinna rugosa*, which are sessile bivalve mollusks harvested for their adductor muscle sold at varying prices in the national and export markets. Fishers use 24 feet-long fiberglass outboard motor boats where divers go underwater to unbury CDHs off sandy bottoms using a rudimentary underwater breathing apparatus called hookah (Basurto 2006). Fishing teams vary in the number of crewmembers and can be conformed based in kinship ties or not. Seri fishing grounds can be partitioned in three different types: "hookah fishing areas" <HookahFishingAreas.Inside.SeriFishingGrounds>, "non-hookah fishing areas" <Non-hookahFishingAreas.Inside.SeriFishingGrounds>, and "no-take fishing areas" <No-takeFishingAreas.Inside.SeriFishingGrounds>. Hookah fishing areas are those places purposely selected by commercial fishermen because they are deemed as especially suitable to harvest CDHs. Non-hookah fishing areas are very shallow and exposed at low tides therefore allowing harvesting CDHs without the use of hookah diving equipment. Finally, no-take fishing areas constitute places where eelgrass areas grow densely and so are generally not targeted for CDH harvesting, given that it is common practice for many divers to walk over the bottom, and diving there is more laborious and presents the risk of stepping on a hidden sting ray or swimming crab. These areas assure that a portion of the fishing stock remains off-limits during part of the year, likely allowing the regeneration of some Seri fishing stock (Basurto 2008). They can cover up to 12% of the Channel's bottom for up to eight months of the year (Torre Cosio 2002).

This community-based fishery is not actively regulated by the federal government <ResourceSystem.CoveredBy.FederalGovernment> and solely self-governed by the Seri community under a common property regimen in the Infiernillo Channel (Figure 1) <ResourceSystem.CoveredBy.CommonPropertySystem>. While all Seri fishers have the right to harvest from any fishing ground inside their common property <SeriFishers.Covers.FishingArea>. The Seri have found it important to design a number of rules—or institutions—to govern the uses of their communal resources (Basurto 2005). One informal rule dictates that hookah divers must not harvest in "non-hookah fishing areas", where traditionally non-commercial fishing members of the Seri community such as women, children, and elders, participate. Community members have a variety of ways to monitor that divers do not brake these rules <Community+Monitors+FishingAreas>, and the Seri government can enforce and sanction rule-breaking of communal rules, especially when non-Seri fishers are caught harvesting Seri fishing areas without explicit permission from the community <SeriGovernment+Sanction+Non-SeriFishers> <NonSeriFishers.Inside.FishingArea$_X$>.

Fishers have developed in-depth knowledge about their fishing areas and the species they harvest, and use such knowledge to govern and manage their fishery. For instance, Basurto (2008) documented more than nine different hookah fishing areas in use between 2000 and 2001, and a similar number of non-hookah fishing areas more recently. Differences in adductor muscle size between *A. tuberculosa* and *P. rugosa*, and among different fishing areas plays an important role in choosing some "hookah fishing areas" over others at particular time periods, and it is likely that fishers practice a haphazard rotation pattern among their hookah fishing areas. Roughly, there are some areas that are used throughout the year

<A.tuberculosa.Inside.FishingArea$_X$> <P.rugosa.Inside.FishingArea$_X$>, other areas that are generally visited once a year <A.tuberculosa.Inside.FishingArea$_X$> <P.rugosa.Inside.FishingArea$_X$>, and yet others visited only once every few years <A.tuberculosa.Inside.FishingArea$_X$> <P.rugosa.Inside.FishingArea$_X$>. So while Seri Fishers know that there are a number of fishing areas of A. tuberculosa that are close to their home village <FishingTeam.Near.FishingArea$_X$>, they might or might not visit them depending on the level of abundance thought to have at that particular moment in time. Similarly some fishing teams are only found in the farthest fishing areas during particular time periods <FishingTeam.Far.FishingArea$_X$>. The selection for harvesting of non-hookah fishing areas is a bit different, given that these are only available at particular low tide periods, making them suitable to manual harvesting. Here some households always visit the same non-hookah fishing area whether is far or close to their home <Household$_X$.Far.FishingArea$_X$>. Some have been doing it for many years and its become a traditional gathering among certain families.

5. Discussion and synthesis

From these case studies we can see the influence of spatial structure and spatial relationships on the function of those systems. The spatial structure and salient spatial relationships necessarily varies across these systems as we intentionally chose case studies that provided some variability in context (irrigation, marine fishery, community forestry). Still we can see some common threads through the application of this ontology to these case studies.

The presentation here does not delve into a quantitative analysis given the small number of case studies described here. Instead we have focused on the challenges of decomposing the system components and characteristics into a framework that would enable quantitative analysis given a sufficient number of cases. However, from this structure a series of coded case studies could be defined by spatial attributes defined in the ontology such as the size of the landscape partition containing a common pool resource. Or the system could be defined by whether the actors live adjacent to the landscape partition containing the common-pool resource (as with the intentional community and the community owned forest) or outside/"far" from the resource (as with the Seri fishers and fishing grounds. These two spatial characteristics are tied to the ability to monitor the activities of users who are allowed to or excluded from harvesting a resource.

Social-ecological systems are inherently complex and the ontology presented here of course simplifies the complexity in these systems. And of course the issue of complexity poses challenges for analysis (Manson 2001) that are not limited to the application described here. In some ways the implemenation of the ontology can be considered a method to simplify the implicit complexity of SESs. Given a sufficiently large sample size analytical methods could then be used to determine which attributes or structures explain dependent variables such as the change in a resource over time. But of course the utility of this approach is limited by the data collected describing a particular SES.

One of the largest obstacles to implementing this ontology for cross-site analysis is the subjectivity involved in deciding which spatial relationships and which actions are to be included or not included. If the analysis were limited to one particular category of SES then it would be plausible to define a set of required relationships to be coded (e.g. <Household.(Near/Far).Canal>). But this would limit cross-site analysis of SES with different resource types. Previous efforts to define frameworks for the analysis of SESs have attempted to find the balance between the desire to have a generalizable framework but also one that is specific enough to capture the salient dynamics in a system. If those salient dynamics are not generalizable across systems then this poses a fundamental obstacle in the implementation of frameworks for the cross-site analysis of SESs.

It can be difficult to decide who to code specific relationships in a system using this framework. For example, in the Seri case described above do households in the community monitor other households <Households.Monitor.Households> or do they monitor the fishing sites<Households.Monitor.FishingGrounds>? Each of these choices is plausible given the definition of the system and the distinction between the two is arguably subtle. A researcher may choose to code both of these in the ontology to provide the most comprehensive definition of the system, but this can increase the effort required to complete the coding. Alternatively a researcher may choose to code just one of these options which could potentially lead to difficulties for cross-site analysis if a researcher defining a similar system chose to code the alternative option. These two relationships could be reconciled after the coding is completed, but it should be acknowledged that relatively subtle differences in how a researcher perceives a system can lead to discrepancies in how that researcher implements the ontology. Future work will include documentation of the ontological framework that documents complete examples of specific case studies as well as user tutorials to address these potential coding problems.

6. Conclusion

We have presented an ontology to define spatial relationships in social-ecological systems with an emphasis on institutional dynamics. We consider this a first step implemented for a series of case studies that are similar in spatial scope (community level) but diverse in the ecological domain (marine, irrigation and forest systems). This work provides a framework that can facilitate the cross-site analysis of social-ecological systems. To date, much of the previous work on institutional dynamics in social-ecological systems has consisted of case studies. Because of the institutional and ecological complexity across case studies, it has been difficult to produce generalizable findings from this literature. This framework contributes to efforts to organize this scientific domain (Anderies, Janssen et al. 2004; Anderies, Rodriguez et al. 2007; Ostrom 2007) by developing a spatially explicit approach to the definition of these systems. The next challenge in this research is to apply this ontology to a larger array of case studies that would enable a more quantitative analysis of the relationships driving the resilience of these systems.

Acknowledgements

We are grateful to numerous colleagues at the Center for the Study of Institutions, Population and Environmental Change and the Workshop in Political Theory and Policy Analysis at Indiana University for extensive discussions that contributed the development of this manuscript. We gratefully acknowledge support from the National Science Foundation (grant <number>), The Wallace Foundation, The Mexican National Council for Science and Technology (CONACyT) and the Christensen Fund which facilitated this work.. We owe the existence of the Tulip Poplar's information to the dataset of the International Forestry Resources and Institutions (IFRI) program and to the many IFRI scholars who have participated in data collection for this project over the last fifteen years, as well as to the database support of Julie England and Robin Humphries. Funding for the IFRI network has been provided by the Food and Agricultural Organization of the United Nations, the Ford Foundation, and the MacArthur Foundation.

Figure 1. Conceptual design of ontological framework

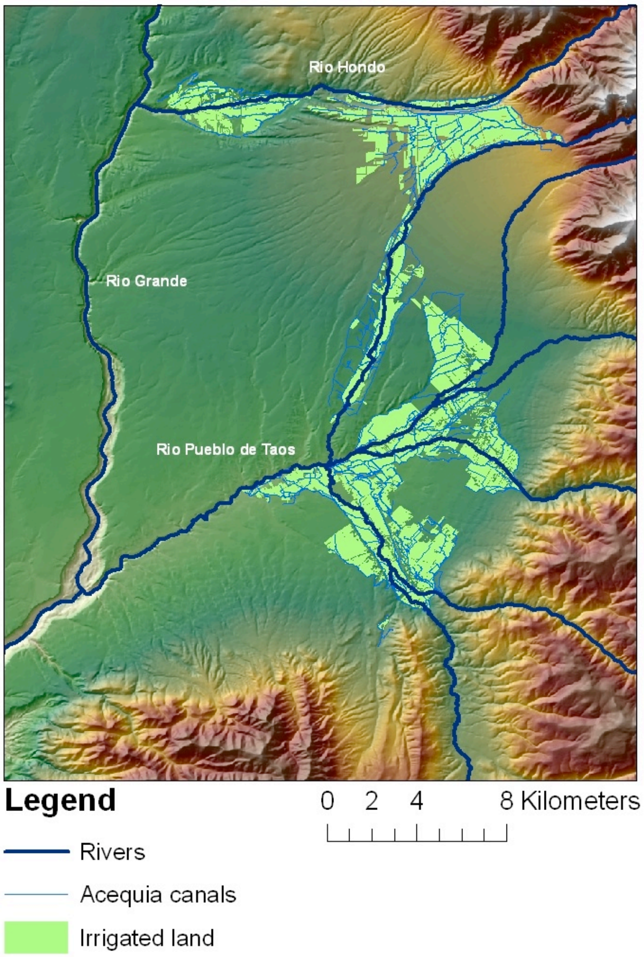

Figure 2. Spatial Structure of Acequia System in New Mexico

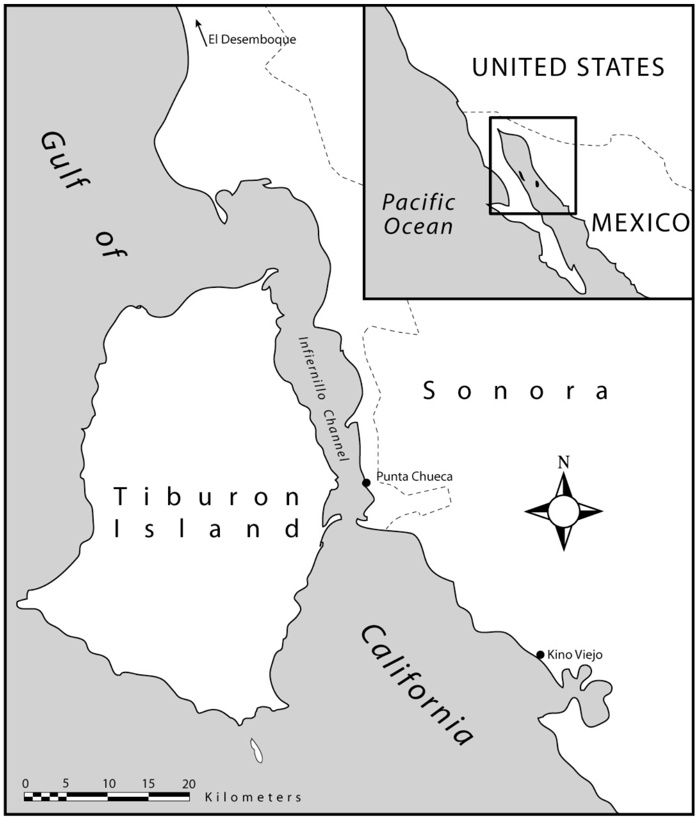

Figure 3. Seri Fishing Community in Gulf of Mexico

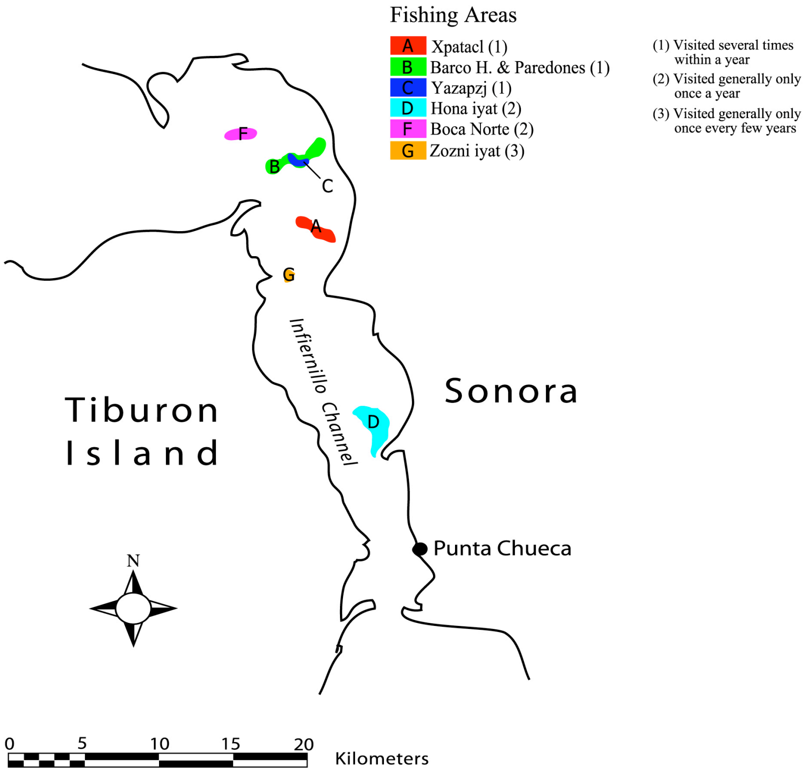

Figure 4. Relative location of community and fishing grounds

Appendix 1. Overview of Spatial Explicit Ontology for Social Ecological Systems

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