New Approaches to the Scientific Study of Religion 7
Series Editors: Lluis Oviedo · Aku Visala

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Human Simulation: Perspectives, Insights, and Applications

Springer

Simulating Religions as Adaptive Systems

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Abstract Religious communities exhibit many features of complex adaptive systems (CASs). They are open systems whose global features nonlinearly emerge from the interactions of their components, are complexly internally structured, and must adaptively respond to continual perturbations in their environments. This chapter presents a system dynamics model (SDM) of a generic religious organization represented as a CAS. The simulated community extracts energy from an ecological resource base and expends energy on distinct, mutually exclusive goals: reproduction, energy-seeking, and ritual. Although energy that is spent on ritual cannot be spent on utilitarian objectives, ritual performance increases the perceived legitimacy of the religious system, thereby motivating higher levels of cooperation. Low levels of perceived legitimacy can trigger a switch to a charismatic version of authority. In experiments, we found that many simulated communities maximized their populations by outstripping their resource base shortly before collapsing, in a classic example of boom-and-bust ecological overshoot. However, certain communities showed greater longevity if the Charisma parameter was maximized. We interpret our results to suggest that increasing social flexibility in response to crises of legitimacy may contribute to the resilience of certain types of social, including religious, systems.

Keywords Complex adaptive system · Religion · Ritual · Charisma · Resource overshoot · Supernatural beings · Structural hierarchy

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S. Y. Diallo et al. (eds.), *Human Simulation: Perspectives, Insights, and Applications*, New Approaches to the Scientific Study of Religion 7,
https://doi.org/10.1007/978-3-030-17090-5_12

Introduction: Complex Adaptive Systems and Religion

For more than a century, scholars have heatedly debated how to define religion. Is religion defined by ritual behaviors? Supernatural beliefs? Institutional forms? For the past generation, the consensus answer to these questions has been "none of the above." Rather, it is assumed that the word "religion" does not refer to a natural kind at all, but instead to an artificial agglomeration of concepts united under a term of convenience for Western scholars (Asad 1993; Smith 1982). According to these critiques, religion is an artifact, not a real thing.

Indeed, religious beliefs and practices do differ radically across cultural, historical, and geographical lines. However, proponents of the strong artifactualist stance fail to account for a great deal of data indicating that religious beliefs and practices vary across cultures in ways that are not random and are often predictable. For example, religious practices that feature spirit possession trance – in which culturally postulated spirits enter practitioners' bodies during music- or drug-induced trance – are significantly more common in structurally complex, hierarchical societies than in small-scale cultures (Bourguignon 1976; Wood and Stockly 2018). Similarly, beliefs in morally concerned gods and punitive afterlives appear to be more common in large-scale cultures based on agriculture and trading than in foraging societies (Douglas 2004; Purzycki et al. 2016). These findings seem to point to flexible, hidden connections between environment, economics, and religious cognition and behavior that make for common patterns of *change* across differing cultures.

The possibility that patterns of dynamic change are where to look for commonalities suggests that religious cultures may be best understood as dynamic systems. In this chapter we present a simulation model of religion as a *complex adaptive system (CAS).* We argue that certain cognitive, behavioral, and social elements dynamically interact according to analogous patterns in all religious systems (and indeed, as we will see, in all cultural systems). Modeling religions as CASs highlights the *structural* similarities that characterize all religious groups – even those that differ drastically in theology, practice, and even scale. At the same time, we hope that it can account for wide (and constantly evolving) variations between different groups, as well as within the same groups at different times, via dynamical alterations in the hidden connections between different constitutive elements. Below, we will describe the core elements that we believe characterize real-world religious systems.

First, however, it is important to describe what complex adaptive systems are, and to explain why that description applies to religious groups. A complex adaptive system is a self-organized arrangement of interrelated elements that uses feedback and adjustment to adapt to its changing surroundings, enabling the system as a whole to persist despite perturbations in its environment and within its own structure. The elements and processes that make up complex adaptive systems are organized into hierarchical structures. Moreover, a CAS is not simply the sums of its parts, nor is the behavior of the whole system a linear product of the individual behavior of its components. In other words, CASs exhibit *emergence*. They are also "open

systems" – that is, they take in material and energy from their environments, use that material and energy to maintain their own internal structure, and emit wastes and other materials back out into their surroundings.

Cybernetic or *control systems* – such as thermostats or refrigerator cooling systems – share some important characteristics with CASs, namely the use of feedback and recursive adaptation to maintain key variables within desired parameters. But while control systems use negative feedback (that is, balancing or dampening functions) and are often subservient to higher-order goals within larger systems, CASs make extensive use of positive (reinforcing) feedback and serve only the goal of their own persistence, making them "general purpose systems" (Rappaport 1979). CASs therefore don't exhibit perfect homeostasis. Instead, their parameters are constantly shifting as they adjust their dynamics, sometimes dramatically, in an attempt to continue existing despite perturbations. The particular historical trajectory of any given CAS therefore is crucial to understanding the details of its current behavior.

Nor are all open systems complex systems. The physical constitution of a sand dune is constantly changing, and its borders aren't crisply defined: the wind continually whisks off old sand and deposits new sand in its place. Over the course of years, the same dune might even cycle through a completely different population of sand grains. However, the dune doesn't have any internal hierarchical structure or exhibit adaptive behavior. It's just the sum of billions of parts. So, while it may be an open system, it's not a complex system.

We argue that religious institutions are complex adaptive systems in that they meet all the criteria listed above (Sosis 2017, 2019; Sosis and Kiper 2014). They are self-organized, are internally structured, and exhibit emergent characteristics (that is, they are more than the sum of their parts). Additionally, religions feature two other important characteristics of complex adaptive systems: they are highly responsive to random environmental fluctuations, and their constituents are not necessarily consciously aware of the adaptive behavior of the systems of which they are part.

The fact that historical trajectories of religious institutions are highly sensitive to random events and environmental fluctuations means that any rigorous analysis of a religious group must be diachronic – that is, it must take into account historical events and contingencies. For example, the highly recognizable anthropomorphic iconic art of Mahayana Buddhism probably emerged from the interaction between Greek and Indian cultures after Alexander the Great's Asian conquests (Marshall 2000). Thus, the widely disseminated Buddhist material tradition of sculptures and paintings of the Buddha was shaped by a highly contingent – and *a priori* unpredictable – historical happenstance. All religious traditions are similarly deeply shaped by unpredictable external "nudges," just as the development of a storm system is shaped by the proverbial butterfly flapping its wings. This sensitivity to seemingly minor influences is a characteristic feature of complex systems.

The constituents of religious systems – that is, their human adherents and members – are also typically unconscious of the adaptive dynamics of the broader systems of which they are part. Hence, while religious systems may behave

in ways that adapt and respond to perturbations and events, these system-level responses often do not result from conscious planning by individual agents, even religious leaders. This is not to deny that formal leadership hierarchies have power to influence the direction of their communities. The papacy exerts tremendous influence on daily life in the Catholic Church, as exhibited by the reforms of Vatican II (although the effects of these reforms may not have been adaptive for the church as an institution; Stark and Finke 2000). However, the advent of charismatic Catholicism, another momentous recent development in the church, was largely the spontaneous product of movements within the laity (Cleary 2018). Charismatic or Pentecostal Christianity has often been described as a populist adaptation to modern, market-based secular society (Dempster 2011). The fact that the rise of charismatic Catholicism immediately followed the Vatican II reforms suggests that it was in part a local response to the liberalization of Catholic doctrine at the level of individual social networks and parishes. Macro-scale shifts in the adaptive dynamics of religious systems often exhibit just this responsive but decentralized character (Sosis 2017).[1]

Religious groups, then, behave in ways that are remarkably similar to standard descriptions of complex adaptive systems. Of course, complex systems differ widely in their composition, structure, and behavior. A human body is a complex adaptive system, since it is hierarchically organized, is adaptive to changing conditions, exhibits emergent effects, takes in material from its environment, and so forth. But the stuff that makes up a human body is organic matter based on carbon compounds, as well as trace minerals and lots of water. What, then, makes up a religious system?

The Elements of the Religious System

Unlike a human body, a religious system is functionally invisible at the everyday level of analysis. One can see church buildings, smell incense smoke, and hear parishioners chanting, but none of these things – nor all of them together – are "the religious community." Most of the elements that make up religious systems are not physical entities at all, but rather *patterns of behavior* and *mental contents*. Specifically, we suggest that the "building blocks" of religious systems are *authority*, *meaning*, *moral obligation*, *myth*, *ritual*, *sanctity*, *supernatural agents*, and *taboo* (Sosis 2017, 2019). Together, these building blocks structure the actions, thoughts, expectations, and values of the individual people who take part in the religious system. The religious system itself, then, consists of the patterned behavior of the people who constitute it, along with the material items and mental representations they generate. The eight building blocks are like rules governing this patterned behavior.

[1]The charismatic Catholic response to shifting social and cultural mores may also be an example of positive feedback driving permanent alterations in the dynamics of religious systems.

In our view, ritual is by far the most important of these eight building blocks. In fact, ritual is the driver of everything else in the religious system. Rituals are tangible, formalized behaviors that indicate that their performers accept the authoritative standards of the community that supports them (Rappaport 1999). Note that this is not the same as saying that performers *believe* the particular theological claims of the religious community. One can easily disbelieve in God while reciting the Jewish sh'ma. But by reciting the sh'ma, one *is* at least indicating a certain level of baseline acceptance of the authority and norms of Judaism. The percentage of one's neighbors who routinely practice the normative religious rituals is thus a good indicator of how much "hold" the religious system has on the community. Ritual probably also serves as a credible signal of commitment (Sosis 2003). As people participate in ritual and see others also participating, they come to see the religious community as more and more relevant, and they feel more invested in it. Ritual is therefore the linchpin that holds together all the other building blocks and "powers" the religious system.

For example, all religious institutions use ritual to reify and shore up non-empirical claims, whether those claims are about the Christian God, the Islamic Allah, or the spirit ancestors of a forager tribe. And while not all religions are strictly concerned with the humanistic moral axioms of Abrahamic and other world religions (such as not harming others), all religious institutions are concerned at some level with *norms*, or the basic expectations for how people ought to behave. For instance, the horticultural Maring people of Papua New Guinea believe in a variety of spirits and pay obeisance to them in rituals, but these spirits do not care much about whether people in the tribe commit adultery or cheat one another (Rappaport 1968). Rather, the spirits are interested in policing the correct role distinctions between men and women and in ensuring that the proper taboos are observed for war and animal husbandry. Thus, moral obligation is a fundamental aspect of all religious systems, despite the fact that what counts as "moral" varies radically across societies (Rappaport 1999).

Taboos, or socially constructed delimitations on behavior that have moral force for the people who abide by them, are another crucial feature of religious systems worldwide. One example is the Jewish kosher proscription against shellfish and pork. Jewish people are perfectly physically capable of eating these things, but because of religious regulations, observant Jews do not, in fact, eat them. Similarly, many religions have bans on sexual activity at certain times of the year or in particular contexts (Boster et al. 1998; Rappaport 1968).

Like taboo, sanctity or sacredness also refers to a socially constructed boundary that bears significant moral weight (Durkheim 2008). Certain objects or persons may be considered sacred and thus inviolable or subject to special treatment. The interior of a church or temple may be considered a sacred space, such that different standards for behavior apply once one has crossed the threshold. In general, things, places, and beliefs are sacred if the values or rules they evoke are not subject to normal utilitarian or rational exchange (Atran and Ginges 2012; Tetlock et al. 2000). An Eastern Orthodox worshiper doesn't treat an icon of Mary with reverence because

somebody is paying her to do so; rather, she treats the icon with reverence because the icon is a sacred object (one that is "set apart," in Durkheim's famous phrasing).

Authority underpins adherence to taboos and sacred values, as well as to ritual, because neither the form nor the content of these elements is determined by natural law. One religious community has a taboo on pork while another has a taboo on beef; one tradition considers Jerusalem a sacred location, while another treats the city of Varanasi with particular reverence. There are almost limitless degrees of freedom in how religious communities carve up the world into sacred and profane, taboo and acceptable, ritual and ordinary action. Authority is what coordinates shared decisions and actions in such contexts – that is, when many potential options are equally viable (Simon 1991). People don't need authority to tell them to run from a burning building, because the option of staying in the building is not reasonable. But people do need authority to tell them which side of the road to drive on, since – although both sides work equally well – the usability of roads depends on everybody driving on the *same* side. Thus, religious communities need some level of authority to consolidate shared conceptions of the sacred and taboo, and to ensure that everyone has the same expectations regarding moral norms, ritual behaviors, and theology. Without authority, no two people will necessarily believe in the same gods or perform the same rituals – in short, there will be no religious system. Authority can take different forms, most saliently in Weber's distinction between *charismatic* authority and other forms of institutional authority (Weber 2012). We will return to this distinction below.

Supernatural beliefs, such as beliefs in gods, ancestors, or spirits, may be partially a natural product of human cognition (Atran 2002; Barrett 2012; although see Wood and Shaver 2018). As such, the *existence* of belief in supernatural beings may not be dependent on any specific authority; yet the particular form that supernatural belief takes is always highly determined by cultural learning and needs behavioral scaffolding for long-term stability (Sosis and Kiper 2018; Willard and Cingl 2017). Thus, determinate supernatural beliefs – such as that God was incarnated in Jesus or that Gabriel dictated the Quran to Mohammad – tend to dissipate wherever religious authority declines (Douglas 2004). In turn, normative supernatural beliefs help legitimate ritual and increase the affective impact of myth (Sosis 2017).

Myths are narratives that evoke, explain, make meaning out of, and legitimate other elements of the religious system, from particular supernatural beliefs to the authorities that lead and direct the community. For example, Jesus' exclamation in Matthew 16:18 that Peter is the "rock" upon which the church will be built has provided narrative legitimation and a sacred context for nearly two millennia of the papacy, construed as a direct continuation of Peter's apostolic leadership. Similarly, the stories about Shiva in the Hindu Puranas both reflect and support the central role of ascetic meditation in Shaivite religion (Doniger 1973). Myths often provide the symbolic and narrative context for rituals, and in many cases may in fact be narrative exegesis of ritual practices (Rappaport 1999). Without the narrative component, a religious system loses its affective grounding and, with it, the power to motivate adherence to sacred customs and rituals.

The final element of the religious system, meaning, is a multifaceted concept that can be defined in many ways. Psychologists have characterized meaning as a sense of purpose or of contributing to an important collective good (Baumeister et al. 2013; Frankl 2006). By contrast, the Durkheimian tradition in social anthropology sees meaning as emerging from socially constructed schemas for the categorization of the social and natural world – that is, it reflects the extent to which the worldview handed down by one's culture "makes sense" despite being socially constructed (Douglas 1986; Durkheim 2008). Bundling these definitions together, we consider meaning to be a cognitive and affective evaluation of the *coherence* of the socially constructed environment. This environment includes both the social structure (including its obligations and roles, which can produce a sense of fulfilling a function or of having a purpose) as well as the categories that help make sense of reality, such as the twin Buddhist concepts of *dukkha* (suffering) and *anatta* (lack of a personal soul). A well-functioning religious system provides meaning in both these senses. Sacred concepts, which create artificial distinctions in the natural world, help drive this effect. For instance, the cycle of Advent, Christmas, Lent, Easter, and ordinary time in the Christian liturgical calendar imposes an artificial set of sacred distinctions on the natural year, and thus makes the passage of time feel more orderly and coherent for Christian adherents.

Together, these eight elements interact in complex ways to produce dynamic systems that govern and order the lives of participants. Ideally, the religious system is well-balanced; it has the proper level of authority, appropriate and compelling myths, a robust ritual life, etc. The people who belong to the system should also feel that they are making a good decision by continuing to belong. If the members of a religious community feel that the community offers sufficient meaning and that the community inhabitants are sufficiently cooperative to succeed in joint endeavors, they will tend to conclude (at a tacit level) that the religious system is legitimate and worth belonging to. However, it is easy for a religious system to become unbalanced and disintegrate by losing its credibility or legitimacy, or by failing to provide for members' basic needs; indeed, most of the religious systems that have ever existed have met with failure, usually quite quickly (Sosis 2017; Sosis and Bressler 2003). Religious systems therefore need to be flexible and able to respond adaptively to challenges and perturbations, such as changes in the economic landscape or declines in popular legitimacy. These attempts to adapt are the features of religious systems that we set out to model.

The Model

The model presented in this chapter is a computational simulation version of a conceptual model described in Sosis (2017; also see Sosis 2019). In that paper, Sosis articulated a feedback system in which agents participate in ritual to generate and perpetuate a religious system. Agents are constantly evaluating the system's effectiveness at delivering biological and social imperatives; in particular, adherents

value cooperative social behavior (Iannaccone 1994) and reproductive coordination (Weeden and Kurzban 2013), as well as indicators of health. If agents perceive that members of a religious community are not successfully cooperating with one another to secure public goods, or that members do not have good reproductive outcomes, then individual agents – both inside and outside the community – will impute less legitimacy to that community. As a result, they may begin to participate less in the normative rituals that sustain its values, norms, and ideals. Without legitimacy or the input of ritual, the religious system is at risk of dissolving, unless a charismatic revival can resolve the problems within the system and motivate ritual participation. On the other hand, if indicators suggest that membership in the religious system will afford the opportunity to socialize with highly cooperative others and to find a mate with a high chance of reproducing successfully, then the system's legitimacy is enhanced, and adherents will be motivated to continue participating diligently in the normative rituals.

In most social contexts throughout history, religious systems have largely overlapped with cultural units at large (Luckmann 1967). Religious systems have therefore also been responsible for the provision of basic economic goods (Goode 1951). Consider the central role that monasteries played in agriculture in the European Middle Ages, or the inseparability of religious rites from hunting practices in many Plains American Indian cultures; for inhabitants of such cultures, religious ritual and basic economic actions are mutually implicated in one another. If the religious system struggles to successfully coordinate the extraction of energy from its environment, it can quickly lose legitimacy and suffer a decline of ritual.

However, all religious systems have access to a potentially powerful tool that can counter declines in legitimacy: charisma. In a Weberian sense, charisma is a source of authority that does not depend on coercion or bureaucratic infrastructure; it is spontaneous, personality-driven, and intrinsically emotionally compelling (Weber 2012). Anthropologists and ethnographers have long noted that social structural hierarchies within societies of all scales are often complemented by social modes that de-emphasize formal structure and allow for spontaneous, egalitarian expression (Turner 1996). This less structured social mode may play an important role in facilitating change and introducing novelty into social systems (Bourguignon 1973). The function of Pentecostalism as a possible worldwide Christian adaptation to the profound changes of urbanization and market integration may be an example of this adaptive process of social change (Dempster 2011). Thus, when a religious system is in decline or has suffered a loss of legitimacy, charismatic leaders or movements may be able to renew levels of commitment, in part by reconfiguring the social system in response to the new environmental conditions.

Using the simulation software AnyLogic V.8.2.3, we built a system dynamics model (SDM) to represent a religious system that matches the descriptions provided above. An SDM model simulates the time-dependent flow of abstract quantities through "stocks," modulated by set parameters and dynamic variables (Forrester 1971). SDMs are commonly used to simulate commercial logistics systems, in which raw materials or finished goods "flow" from sources to warehouses to retail outlets. Variables such as weather or fuel costs influence the rate at which goods

flow, and are constantly changing in relation to each other and other variables. Topically for our present purposes, SDMs are also commonly used to simulate the flow of energy, resources, and population within complex social and ecological systems (Forrester 1973).

Our SDM centers on two stock-and-flow subsystems, one of which represents the flow of caloric energy through a social system, and the other of which represents the flow of population (see Fig. 1). Resources are extracted from a Resource Base and flow into a stock called Available Energy. Once these energy resources are available to the community, they can be used in one of four ways: (1) reproductive effort; (2) further energy-seeking (such as farming or hunting); (3) personal consumption for basic bodily needs; and (4) religious or cultural ritual. The Resource Base itself is renewed at a rate controlled by the parameter "Ecological Carrying Capacity." In a separate stock-and-flow diagram, persons can enter the community either through birth or through conversion, and depart either through death or through apostasy (de-conversion).

The simulation model hinges on constant adjustments to the rates of flow through the energy and population stocks, governed by a number of variables and parameters. Parameters are static and constant within each model run, while variables are dynamic and constantly changing (see Tables 1, 2 and 3). The most central variable is Legitimacy, a multiplicative combination of Health (the difference between births and deaths), Meaning, and an assessment of the level of cooperation and coordination within the community. Legitimacy represents the extent to which members of the religious system feel committed to its norms and beliefs. Legitimacy increases Ritual Participation. The ratio between Ritual Participation and Reproductive Effort plus Energy Seeking generates a "Ritual Buy-In" variable, which represents the extent to which community members are willing to devote their energy to normative ritual as opposed to other biologically important activities. In turn, Ritual Buy-In partially determines the value of a Stag Hunt variable, which represents the proportion of economically productive activity that is carried out in close coordination with others. Higher values for the Stag Hunt variable lead to a higher return rate for efforts to secure energy.

A similar variable, K Rate, represents the proportion of high-investment to low-investment mating activity. In accordance with life history theory, higher values for this variable reduce the rate of reproductive effort, effectively increasing Ritual Buy-In (see Baumard and Chevallier 2015). Like most other variables in this model, K Rate and Stag Hunt vary between 0 and 1, since they represent *proportions* of energy devoted to particular strategies. The sum of these two variables produces CCB Assess – the variable that reflects the community's level of cooperation and coordination. Higher levels of CCB Assess lead to higher values for Legitimacy – which in turn produces higher levels of ritual participation, leading in turn to higher values for Stag Hunt. This is a classic example of a positive feedback loop.

Stag Hunt is also influenced by Moral Obligation, on the assumption that higher levels of felt obligation will produce more high-return cooperative and coordinated economic activity (e.g., hunting a stag with four others rather than hunting a rabbit alone). Moral Obligation is in turn calculated as the mean of Authority, Ritual, and

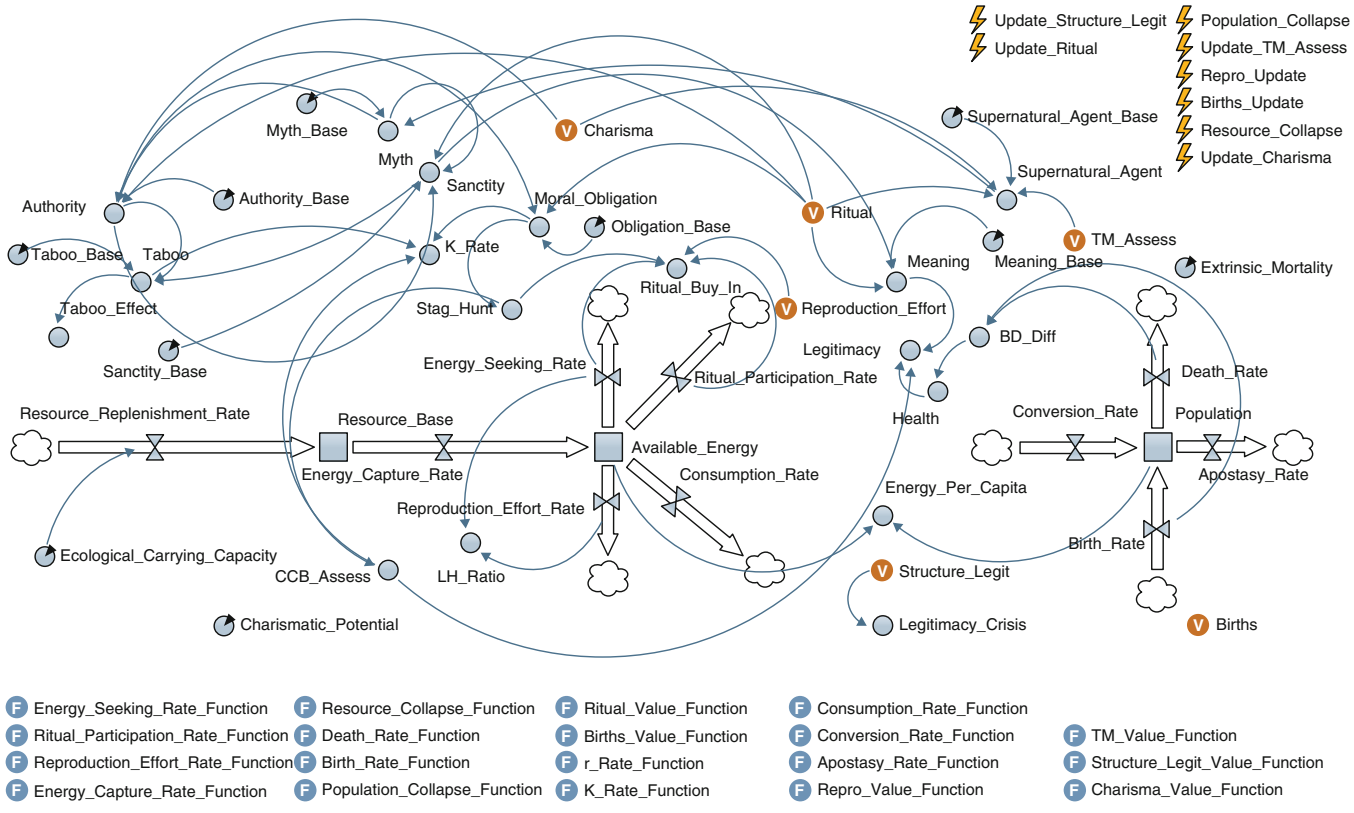

Fig. 1 Simulation schematic
Visual schematic of the simulation model presented in this chapter. Functions are listed along the bottom. Events are on the top right. Parameters are circles with wedges, while circles without wedges are dynamic variables. Circles marked "V" are variables that are updated periodically (not at every time step)

Table 1 Model parameters

Parameter	Range Min	Range Max	Qualitative description
Ecological_Carrying_Capacity	10	1000	Sets upper bound of resource replenishment rate
Taboo_Base	0.01	0.99	Sets baseline value for taboo variable before dynamic effects
Meaning_Base	0.01	0.99	Sets baseline value for meaning variable before dynamic effects
Myth_Base	0.01	0.99	Sets baseline value for myth variable before dynamic effects
Obligation_Base	0.01	0.99	Sets baseline value for obligation variable before dynamic effects
Authority_Base	0.01	0.99	Sets baseline value for authority variable before dynamic effects
Sanctity_Base	0.01	0.99	Sets baseline value for sanctity variable before dynamic effects
Supernatural_Agent_Base	0.01	0.99	Sets baseline value for supernatural agent variable before dynamic effects
Charismatic_Potential	0.01	0.99	Determines effect of legitimacy crisis on Charisma
Extrinsic_Mortality	1.00	1.99	Sets baseline for death rate

All model parameters with their possible ranges and qualitative descriptions of their effects within the simulation

a baseline parameter. All variables reflecting core elements of the religious system other than ritual are partially constrained by parameters that give baseline values; for example, there is an Authority Baseline and a Taboo Baseline. These parameters provide the bounds for each model run, and allow us to test the model's behavior by searching for the combination of parameters that generates desired outcomes.

K Rate is also influenced by Moral Obligation, as well as by Taboo (the mean of Sanctity, Authority, and the Taboo Baseline). Because religious taboos often constrain economic and sexual activity, Taboo restricts the Energy Capture Rate as well as Reproduction Effort. Sanctity is the mean of Ritual, Authority, Myth, and the Sanctity Baseline. Along with Ritual and the Meaning Baseline, Sanctity also increases Meaning, thus enhancing Legitimacy. Myth is the mean of Supernatural Agent and the Myth Baseline; it increases both Authority and Sanctity.

Authority, in turn, is the mean of the Authority Baseline, Ritual, and Myth – but with a catch. Charisma, a unique variable that is only activated during crises of religious legitimacy, *detracts* from Authority, while *increasing* Supernatural Agent beliefs. Crises of legitimacy occur when the value of the Legitimacy variable declines below the value of the Authority variable – that is, when the structural hierarchy outstrips its popular support. When crises of legitimacy erupt, Charisma is activated. The value of the Charisma variable is determined by the Legitimacy Crisis variable, as well as by a Charisma Potential parameter. Higher values for this parameter mean that Charisma will exert a stronger effect whenever activated.

Table 2 Model variables

	Formula	Description	Qualitative notes
Taboo	(Taboo_Base + sanctity + authority)/3	Decreases taboo effect; increases K rate	Represents taboos that constrain economic and sexual activity by imposing artificial category boundaries on environment
Taboo_Effect	1-taboo	Reduces the impact of energy seeking rate on energy capture rate; impedes reproduction effort rate	Translates value of taboo variable into implementable form for influencing energy capture and reproduction effort rates
Authority	(Authority_Base + ritual + mythCharisma)/3	Increases taboo, sanctity, moral obligation, and ritual participation rate; decreases structure legit	Represents structural authority (formal religious authority)
Myth	(Myth_Base + Supernatural_Agent)/2	Increases sanctity and authority	Represents legitimating and motivating stories
Sanctity	(Sanctity_Base + ritual + authority + myth)/4	Increases taboo and meaning	Represents salience of sacred/profane distinctions in religious worldview
Moral_Obligation	(Obligation_Base + ritual + authority)/3	Increases K rate and stag hunt	Represents social and internal pressure to behave cooperatively in energy acquisition and mating
Meaning	(Meaning_Base + ritual + sanctity)/3	Increases legitimacy	Represents subjective sense of purpose and place, as well as the subjective coherence of socially constructed categories
Supernatural_Agent	Min(1,(Supernatural_Agent_Base + ritual + TM_Assess + Charisma)/3)	Increases myth and ritual participation rate	Represents belief in socially normative supernatural beings, e.g., sanctioned ancestors, gods, spirits
Ritual_Buy_In	Min(1,(Ritual_Participation_Rate/((Reproduction_Effort*2) + Energy_Seeking_Rate)))	Increases stag hunt	Represents energy investment in religiously normative ritual compared with investment in other biologically crucial activities
Stag_Hunt	(Ritual_Buy_In + Moral_Obligation)/2	Increases effect of population on energy seeking rate; increases effect of energy seeking rate on energy capture rate; increases CCB assess	Represents high-return energy acquisition strategies that require extensive collaboration and coordination

K_Rate	(Moral_Obligation + taboo)/2	Decreases effect of population on reproduction effort rate; increases CCB assess	Represents high-investment, high-cooperation mating strategies
Legitimacy_Crisis	(1/Structure_Legit)	Increases Charisma	Represents extent to which structural authority has outstripped its legitimacy
BD_Diff	Max(0.01,(Birth_Rate-Death_Rate))	Increases health	If deaths outnumber births, community health is construed as low
Health	Min(1,(2*BD_Diff))	Increases legitimacy and conversion rate	Represents the assessment of expected health in the community
Legitimacy	(6*CCB_Assess)*(health) *(2*max(0.1,Meaning))	Increases ritual participation rate; decreases apostasy; increases structure legit	Represents imputed legitimacy of the religious community's norms, beliefs, and structure
CCB_Assess	K_Rate + Stag_Hunt	Increases legitimacy and conversion rate	Cooperation and coordination assessment: Reflects members' evaluations of amount of successful cooperation within religious community
LH_Ratio	Energy_Seeking_Rate/ Reproduction_Effort_Rate	Output only	Life history ratio: reflects the proportion of available energy dedicated to energy acquisition relative to proportion dedicated to mating effort
Energy_Per_Capita	Max(0,(Available_ Energy/population))	Increases conversion rate; decreases death rate; places boundary limits on reproduction effort rate	Represents success of energy acquisition efforts relative to population size

(continued)

Table 2 (continued)

	Formula	Description	Qualitative notes
Charisma	IF Legitimacy_Crisis ≥1 THEN (Legitimacy_Crisis/10) *Charismatic_Potential	Decreases authority; increases Supernatural_Agent	Represents alternative forms of religious authority, based on personality or religious experience, that challenge structural authority
Ritual	Ritual_Buy_In	Increases meaning, supernatural agent, and moral obligation	Represents instantaneous effect of recent trends in ritual participation
Reproduction_Effort	Reproduction_Effort_Rate	Decreases ritual buy-in	Instantaneous measure of recent trends in mating effort
TM_Assess	1-health	Increases supernatural agent	Represents assessment of lethality of environment. TM = terror management
Structure_Legit	Max(0.1,(legitimacy-authority))	Decreases legitimacy crisis	Represents extent to which formal authority is supported by proper levels of legitimacy
Births	(Reproduction_Effort_Rate/16)* (population/18)	Determines birth rate	Instantaneous measure of recent trends in mating effort and population size

All dynamic and updated variables with formulae, descriptions of effects, and qualitative notes

Table 3 Model flows and stocks

Flow rate	Formula
Resource_Replenishment_Rate	Ecological_Carrying_Capacity
Energy_Seeking_Rate	(population*(1 + Stag_Hunt))
Reproduction_Effort_Rate	IF Energy_Per_Capita >1 THEN population*(.1 + (1-K_Rate))*Taboo_Effect; ELSE .01
Energy_Capture_Rate	IF Resource_Base >0) THEN (Energy_Seeking_Rate*(1.6 + (Stag_Hunt)) *(1 + Stag_Hunt)*(1 + Stag_Hunt)*(1 + Stag_Hunt) *(Taboo_Effect)); ELSE min(Resource_Replenishment_Rate, ((Energy_Seeking_Rate*(1.6 + (Stag_Hunt)) *(1 + Stag_Hunt)*(1 + Stag_Hunt)*(1 + Stag_Hunt) *(Taboo_Effect))))
Ritual_Participation_Rate	IF Energy_Per_Capita >0 THEN max(0,((population) *((legitimacy+authority+myth+Supernatural_Agent)/ (max(4,(legitimacy_Crisis/1.5)))))); ELSE max(0,((Energy_Per_Capita)*(population)*((legitimacy +Legitimacy+authority+myth+Supernatural_Agent)/ (max(4,(Legitimacy_Crisis/1.5))))))
Consumption_Rate	IF Available_Energy > population THEN population; ELSE Energy_Per_Capita*population
Conversion_Rate	(CCB_Assess*health) + (Energy_Per_Capita)
Birth_Rate	(births)
Apostasy_Rate	Max(0,((2/CCB_Assess) + (1/legitimacy)))
Death_Rate	Max(0,((3/Energy_Per_Capita)*Extrinsic_Mortality))
STOCK VALUE	Formula
Resource_Base	d(x)/dt = Resource_Replenishment_Rate - Energy_Capture_Rate
Available_Energy	d(x)/dt = Energy_Capture_Rate - Ritual_Participation_Rate - Consumption_Rate - Energy_Seeking_Rate - Reproduction_Effort_Rate
Population	d(x)/dt = Conversion_Rate + Birth_Rate - Apostasy_Rate - Death_Rate

All model flows and stocks with formulae determining updated value at each time step

Finally, Supernatural Agent (supernatural beliefs) is governed by a baseline parameter, Ritual, and a variable that reflects the salience of mortality. This mortality variable is informed by terror management theories of religion, which posit that beliefs in supernatural concepts are, in part, a psychological protection against thoughts of demise (Vail et al. 2010). Mortality rates are governed by an Extrinsic Mortality parameter (higher values for which represent more lethal environments) and a measure of Energy Per Capita. When Energy Per Capita drops below one (a starvation scenario), Mortality greatly increases. Birth Rate is a function of population size and reproductive effort. Conversion Rate is given by the CCB Assess variable, Health, and Energy Per Capita, while Apostasy Rate is given by an inverse

of the CCB Assess variable plus the inverse of Legitimacy – thus, as Legitimacy and cooperation decline, departures from the community increase.

Model Testing

This section presents preliminary tests of this model. For optimization experiments, we identified a target outcome. The optimization engine in the AnyLogic simulation platform tested many combinations of parameters to determine which combination maximized or minimized the requested outcome. For the primary optimization experiments, we attempted to alternately maximize and minimize the size of the population in the community at 250 time steps, representing approximately 20 simulated years. To be accepted, experimental results needed to meet two feasibility conditions: at the end of 250 time steps, simulated communities must still have sufficient energy, and their population must not have dropped below 10. Parameter combinations that failed to meet these conditions were rejected.

The optimization engine was able to identify a wide variety of combinations of parameters settings that maximized population size. Table 4 presents the first 6 feasible combinations of parameters that produced high population levels at 250 time steps. After identifying each parameter combination, we then ran a simulation with no time limits to determine when the simulated religious system would collapse. Collapse is defined in the model as a drop of Population below 2 or a drop of Available Energy below .01. In the simulation, these conditions are implemented as events, Resource Collapse and Population Collapse, which terminate the simulation if the Population or Available Energy stocks drop below a critical threshold. We then maximized the value of the Charismatic Potential parameter while holding the

Table 4 Optimization results for maximized population

Ecological_Carrying_Capacity	183.991	521.441	1000	65.14	324.286	357.661
Taboo_Base	0.339	0.341	0.192	0.201	0.202	0.155
Meaning_Base	0.957	0.287	0.373	0.635	0.713	0.773
Myth_Base	0.99	0.704	0.268	0.721	0.62	0.903
Obligation_Base	0.99	0.824	0.67	0.785	0.706	0.664
Authority_Base	0.505	0.325	0.915	0.568	0.634	0.509
Sanctity_Base	0.677	0.854	0.088	0.16	0.51	0.164
Supernatural_Agent_Base	0.01	0.798	0.99	0.419	0.664	0.536
Charismatic_Potential	0.99	0.337	0.56	0.847	0.464	0.641
Extrinsic_Mortality	1.99	1.47	1.871	1.798	1.817	1.53
Population objective	51.977	2047.284	1016.615	251.167	301.529	307.943
Time at collapse	Stable	251.40	252.02	250.58	261.40	261.52
Collapse time w Max Charisma	.	460.83	148.10	271.70	519.96	688.32

Parameter settings given for first 6 feasible optimization results, including time at collapse and time at collapse with maximized Charismatic Potential parameter

Table 5 Optimization results for minimized population

Ecological_Carrying_Capacity	78	99.55
Taboo_Base	0.01	0.08
Meaning_Base	0.99	0.54
Myth_Base	0.99	0.73
Obligation_Base	0.99	0.46
Authority_Base	0.01	0.32
Sanctity_Base	0.01	0.04
Supernatural_Agent_Base	0.01	0.34
Charismatic_Potential	0.99	0.82
Extrinsic_Mortality	1.99	1.65
Population objective	22.638	27.961
Time at collapse	Stable	Stable
Collapse time w Max Charisma	.	.

Parameter settings given for only 2 feasible optimization results. Both parameter combinations produced stable communities (no collapse)

others constant and reran the simulation to determine whether higher intensities of potential charismatic revival could increase the survivability or robustness of the simulated system. One simulated community was stable – it never collapsed. Of the 5 remaining communities, maximizing the Charismatic Potential parameter led to longer community duration in four cases.

We then asked the optimization engine to minimize the population value, without collapsing the simulated societies (that is, simulated communities must have at least 10 people remaining in the Population stock at the conclusion of time step 250). The engine identified only two combinations, both of which were stable (see Table 5). A statistical analysis of the difference between high-population and low-population simulated communities was not feasible based on these optimization experiments, but qualitative assessment of these results suggests that larger communities may be characterized by higher baseline levels of Taboo, Authority, Sanctity, and Supernatural Agent beliefs.

Next, we optimized the simulation for maximizing the value of the Legitimacy variable at 250 time steps. Multiple combinations of parameters were feasible. We present the results for the initial 6 feasible results in Table 6. Three of the 6 parameter combinations produced stable communities that never collapsed when allowed to run without time constraints. Maximizing the Charismatic Potential parameter led to longer community duration in simulations with no time constraints in two of the three unstable communities.

Finally, we attempted to minimize the value of the Legitimacy variable. The first 6 combinations identified by the optimization engine are presented in Table 7. Four of the six communities were stable when simulation runs were unconstrained by time. Of the two unstable communities, only one was longer-lived when the Charismatic Potential parameter was maximized.

Table 6 Optimization results for maximized legitimacy

	Max legit					
Ecological_Carrying_Capacity	648.879	314.948	172.83	200.167	146.541	596.132
Taboo_Base	0.222	0.696	0.178	0.087	0.039	0.268
Meaning_Base	0.566	0.26	0.452	0.021	0.293	0.054
Myth_Base	0.206	0.908	0.324	0.854	0.751	0.191
Obligation_Base	0.955	0.96	0.517	0.76	0.89	0.86
Authority_Base	0.688	0.883	0.112	0.167	0.257	0.897
Sanctity_Base	0.603	0.315	0.448	0.943	0.254	0.367
Supernatural_Agent_Base	0.626	0.742	0.664	0.712	0.64	0.012
Charismatic_Potential	0.789	0.693	0.72	0.015	0.217	0.677
Extrinsic_Mortality	1.407	1.155	1.789	1.389	1.239	1.225
Legitimacy objective	14.672	2.195	3.213	11.425	2.273	2.743
Population objective	271.537	80.821	42.797	311.808	37.538	102.815
Time at collapse	512.130	Stable	Stable	259.000	Stable	270.610
Collapse time w Max Charisma	574.860	.	.	228.190	.	540.090

Parameter settings given for first 6 feasible optimization results, including time at collapse and time at collapse with maximized Charismatic Potential parameter

Table 7 Optimization results for minimized legitimacy

	Min legit					
Ecological_Carrying_Capacity	226.106	111.895	115.517	83.915	166.52	448.14
Taboo_Base	0.233	0.529	0.244	0.795	0.92	0.57
Meaning_Base	0.752	0.439	0.032	0.165	0.88	0.47
Myth_Base	0.589	0.808	0.602	0.125	0.12	0.4
Obligation_Base	0.416	0.878	0.853	0.856	0.99	0.76
Authority_Base	0.942	0.857	0.186	0.039	0.44	0.93
Sanctity_Base	0.893	0.485	0.929	0.069	0.58	0.12
Supernatural_Agent_Base	0.947	0.143	0.923	0.834	0.2	0.95
Charismatic_Potential	0.783	0.948	0.043	0.875	0.14	0.08
Extrinsic_Mortality	1.478	1.244	1.125	1.92	1.45	1
Legitimacy objective	2.479	0.657	1.204	0.361	1.593	0.059
Population objective	57.100	33.721	32.887	26.772	49.588	11.665
Time at collapse	Stable	1387.350	Stable	Stable	Stable	395.170
Collapse time w Max Charisma	.	972.520	.	.	.	528.500

Parameter settings given for first 6 feasible optimization results, including time at collapse and time at collapse with maximized Charismatic Potential parameter

While the effect of the Charismatic Potential parameter on model performance was mixed across all optimization experiments, a certain subset of simulations appeared to be strongly impacted by increases in this parameter: those (shown in Table 4) that led to community collapse shortly after the targeted time step of 250. These parameter combinations were selected by the optimization engine because they produced high values for the Population stock at the conclusion of the

simulated timeframe; however, these high values resulted from a sudden population spike that, when allowed to play out without time constraints, triggered a resource overshoot and community collapse shortly thereafter (within 25 time steps). Based on the initial six optimization runs for maximized population, these communities appeared to show signs of benefiting from higher levels of Charismatic Potential (that is, enduring longer in unconstrained simulations). We therefore identified an additional 9 parameter combinations that matched this pattern and tested the effects of maximized Charismatic Potential parameter value on these simulated communities (see Table 8). Of the 14 total combinations that produced simulated communities that collapsed shortly after the 250th time step, 12 were longer-lived – some quite significantly – when the Charismatic Potential parameter was boosted to its maximum value of .99.

Conclusion

Modeling religious communities as complex adaptive systems provides a unique window into their behavior and internal structure, one that emphasizes the dynamic relationships between core elements in a context of survival or disintegration. This conception of religions as *autopoietic* systems (Maturana and Varela 1980) enables an epistemic realism about groups that is typically missing from deflationary critiques of "religion" as a category, yet which does not easily succumb to overenthusiastic essentialism. Debates about the meaning of the term "religion" have been important for discarding previous, naïve conceptions that were often based on Protestant assumptions about the primacy of propositional beliefs and religious experience (Asad 1993). Yet these same debates have obscured research in anthropology as well as the biological and cognitive sciences indicating that the characteristics we associate with religion – such as ritual, taboo, and "supernatural" beliefs – are simply core features of human social organizations in general, from tribes or nation-states to the neighborhood church (Anderson 1991; Bloch 2008; Wood 2017).

At all scales, human social organizations adjust their behavior in response to environmental or internal perturbations, all the while using socially constructed norms, beliefs, and categories to "overlay" a human cognitive world atop the natural one (Rappaport 1979; Searle 1995). The feedback between ritual performance, biologically relevant outcomes, and felt commitment to the socially constructed cognitive world is the conduit between objective facts and subjective social reality. This conduit enables the system to dynamically adjust to changes in its objective situation, thereby reassuring its individual members that their biological prerogatives are safe – yet without exposing the transactional or utilitarian dimension to excessive, potentially destabilizing rational scrutiny (Shaver et al. 2017; Morgan et al. 2018). In other words, the autopoietic generation of socially constructed worlds that are nevertheless situated in objective environments depends on the true features of those objective environments remaining partially concealed

Table 8 Test of Charisma effect

MAX POP														
Ecological_Carrying _Capacity	521.441	1000	324.286	357.661	65.14	528.725	246.473	72.031	523.932	65.139	246.72	449.539	74.573	255.245
Taboo_Base	0.341	0.192	0.202	0.155	0.201	0.343	0.082	0.197	0.147	0.078	0.344	0.035	0.195	0.331
Meaning_Base	0.287	0.373	0.713	0.773	0.635	0.865	0.084	0.821	0.01	0.594	0.729	0.011	0.77	0.129
Myth_Base	0.704	0.268	0.62	0.903	0.721	0.792	0.869	0.92	0.791	0.768	0.943	0.907	0.93	0.94
Obligation_Base	0.824	0.67	0.706	0.664	0.785	0.872	0.75	0.742	0.794	0.75	0.776	0.912	0.746	0.737
Authority_Base	0.325	0.915	0.634	0.509	0.568	0.099	0.195	0.566	0.14	0.553	0.492	0.244	0.518	0.886
Sanctity_Base	0.854	0.088	0.51	0.164	0.16	0.802	0.765	0.164	0.048	0.23	0.214	0.107	0.169	0.208
Supernatural_Agent _Base	0.798	0.99	0.664	0.536	0.419	0.778	0.851	0.412	0.782	0.268	0.412	0.071	0.419	0.31
Charismatic_Potential	0.337	0.56	0.464	0.641	0.847	0.424	0.254	0.858	0.424	0.868	0.643	0.981	0.827	0.318
Extrinsic_Mortality	1.47	1.871	1.817	1.53	1.798	1.475	1.445	1.917	1.478	1.99	1.932	1.409	1.864	1.784
Time at collapse	251.40	252.02	261.40	260.00	250.58	260.58	260.53	250.76	264.36	251.24	258.77	250.96	250.91	260.68
Collapse time w Max Charisma	**460.83**	148.10	**519.96**	**688.32**	**271.70**	**747.41**	22.80	**353.37**	**1178.61**	**635.81**	**903.10**	**253.54**	**375.45**	**471.58**

Results for 14 parameter combinations for simulated communities that collapsed shortly after 250th time step (within 25 time steps). Bolded cells along the bottom row indicate simulated communities that survived longer when values for the Charismatic Potential parameter were maximized while holding all other parameter values constant, and allowing simulation to run without time constraints

behind affectively compelling social constructions, which the individual members themselves cooperate in propping up.

The simulation presented here succeeded in capturing some important aspects of the posited complex adaptive system. It tethers together resource extraction and energy use (objective environmental facts) with socially constructed variables, including supernatural beliefs, taboos, and meaning, and provides credible depictions of how these two kinds of variables play off of one another dynamically. Because the simulated system gains and loses members both biologically and through conversion or apostasy, it may best represent scenarios in which competing religious communities both produce their own resources and compete within a wider social context for converts, such as the nineteenth-century religious commune craze in the United States, which one of us has previously studied (Sosis and Bressler 2003). The fact that the current model is well-suited to simulate such a scenario was not intended, but emerged naturally from attempts to computationally implement the theory offered in Sosis (2017, 2019).

One striking feature of the present simulation model is the dramatic way in which it illustrates resource overshoot and collapse. In the first versions of the final model, we noted that populations and resource bases could withstand sudden constriction of resource inflow, adjusting their dynamics to deal with the new scarcity – but only up to a point. Resource or population crashes occurred when resources were suddenly constricted by too large a proportion relative to their previous availability. This effect exhibited something like hysteresis; that is, thresholds for effects depended on the model's immediate history and recent direction. In the final version of the simulation, many population crashes similarly resulted from long-term buildups in the resource base, which eventually made possible sudden steep increases in energy harvest and population growth, thus overshooting the resource base. Once the point of declining returns was met and the resource base reverted to its default carrying capacity, the population and energy requirements were now too great to be supported by the basic carrying capacity of the environment, despite the fact that previously that same carrying capacity had been sufficient to support it. That higher levels of religious charisma in the simulated social systems postponed these crashes is interesting, but not necessarily comforting – the crashes inevitably did come, and were often simply more dramatic. Correctly interpreting these results is a challenging task, but they may imply that increasing the flexibility and adaptability of a social system in response to crises of legitimacy can increase the longevity of that system, though with the danger of even more dramatic eventual collapse. Future versions of the model should attempt to identify variables that more realistically simulate feedback between environmental features and social constructions in the face of resource instability and crises of legitimacy – dangers that are all too familiar to inhabitants of the democratic world in the early twenty-first century.

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