Trade, territoriality, alliances and conflict : complexity science approaches to the archaeological record of the U.S. southwest with a case study from Languedoc, France

Stefani Allison Crabtree

UNIVERSITE DE FRANCHE-COMTÉ

ÉCOLE DOCTORALE «LANGAGES, ESPACES, TEMPS, SOCIETÉS»

Thèse en vue de l'obtention du titre de docteur en

ARCHÉOLOGIE, TERRITOIRES, ENVIRONNEMENT

TRADE, TERRITORIALITY, ALLIANCES AND CONFLICT : COMPLEXITY SCIENCE APPROACHES TO THE ARCHAEOLOGICAL RECORD OF THE U.S. SOUTHWEST WITH A CASE STUDY FROM LANGUEDOC, FRANCE

ECHANGES, TERRITORIALITÉ, ALLIANCE ET CONFLIT : APPROCHE PAR LES SCIENCES DE LA COMPLEXITÉ DES DONNÉES ARCHÉOLOGIQUES DU SUD-OUEST DES ETATS-UNIS ET D'UNE ÉTUDE DE CAS EN LANGUEDOC (FRANCE)

Présentée et soutenue publiquement par

Stefani CRABTREE

Le 14 novembre 2016

Sous la direction de M. le Professeur François FAVORY

Membres du jury :
Laure NUNINGER, Ph.D., Chargée de recherche au CNRS, Archéologie, Université Bourgogne-Franche-Comté
Timothy KOHLER, HDR, Professeur, titulaire de chaire, Anthropology, Washington State University, Pullman
Andrew DUFF, HDR, Professeur, titulaire de chaire, Anthropology, Washington State University, Pullman
Michelle HEGMON, HDR, Professeure, Anthropology, Arizona State University, Tempe, rapporteure
Thérèse LIBOUREL, HDR, Professeure émérite, Informatique, Université de Montpellier, rapporteure

TRADE, TERRITORIALITY, ALLIANCES AND CONFLICT : COMPLEXITY SCIENCE APPROACHES TO THE ARCHAEOLOGICAL RECORD OF THE U.S. SOUTHWEST WITH A CASE STUDY FROM LANGUEDOC, FRANCE

ECHANGES, TERRITORIALITÉ, ALLIANCE ET CONFLIT : APPROCHE PAR LES SCIENCES DE LA COMPLEXITÉ DES DONNÉES ARCHÉOLOGIQUES DU SUD-OUEST DES ETATS-UNIS ET D'UNE ÉTUDE DE CAS EN LANGUEDOC (FRANCE)

By

STEFANI ALLISON CRABTREE

A dissertation submitted in partial fulfillment of
the requirements for the degree of

DOCTOR OF PHILOSOPHY

WASHINGTON STATE UNIVERSITY
Department of Anthropology

&

UNIVERSITE DE FRANCHE-COMTE
Maison des Sciences de l'Homme et de l'Environnement

DECEMBER 2016

To the Faculty of Washington State University:

The members of the Committee appointed to examine the dissertation of STEFANI ALLISON CRABTREE find it satisfactory and recommend that it be accepted.

Timothy A. Kohler, Ph.D., Chair

François Favory, Ph.D.

Laure Nuninger, Ph.D.

Andrew I. Duff, Ph.D.

ACKNOWLEDGEMENTS

In 2012 when Tim asked me if I'd like to do a *cotutelle,* or double Ph.D., maybe I should have run away. But I was curious what it would take, and what it would be like, to be Doctor Doctor. In retrospect maybe Tim wishes he hadn't offered. I recognize the amount of extra time he has put into mentoring me for this wild ride, and I am grateful. One probably shouldn't wax poetic about their advisor, but for the past 7 ½ years it has been a great pleasure to have him as my mentor, my boss, my friend. Thanks for shaping me into the scholar I am today.

This work could not have been completed without Laure Nuninger, my brilliant, caring, passionate and adventurous chef de thèse who ushered me through innumerable hours of burreaucracy in France, who has read every bad draft of poorly written French I have done, and who has forever shaped my thoughts on the prehistory of France, and on archaeology in general. I am very grateful that you are my co-advisor.

François Favory, likewise, has been a steady rock throughout the process of both writing this dissertation, and developing my mind as a young scholar. I am proud to be one of your last students, and hope that your retrait will be lovely once you stop having to read drafts from me.

Andrew Duff has been such a calming presence in this madness. His insight into understanding vastly different types of archaeology has been immeasurable in my studies. Thank you for your help, for reading every draft, and for helping calm me down as I went through the Ph.D. process.

Outside of my committee there are probably hundreds of people who I should thank. First and foremost is Alexander Cragg, my partner, who moved from beautiful Boulder CO to… a less exciting Pullman, WA… all so I could finish my Ph.D. You have helped me through all the ups and downs with enough levity and a healthy dose of sillies, that I actually am making it out the other side both sane (if that's possible) and happy.

Grad school can be a lonely time, and I've heard they don't give Ph.Ds to the smartest people—they give them to the most stubborn. But it really helps to have others going through the same thing with you. Katie Harris, thank you for going through all the shenanigans with me. While I don't want to do this wild ride again, I'd love to do any future crazy undertakings by your side.

Kyle Bocinsky, thank you for helping me learn code, learn logic, and for being my friend. Kristin Safi, my fellow Southwest-lady, I'm so glad we were put in each others' paths, and I'm looking forward to a lifetime of being colleagues and friends. Natalie Fast Clark, you got me through my M.A., and I'd never be where I am now if you hadn't helped me there. I am so glad you're my friend. Kelsey Reese! I'm so grateful for you, and wish you the best in getting your Ph.D. at Notre Dame. Stay stubborn. You've got this. My other labmates, Katie G. and Laura E., thanks for being there, for listening, for helping. Katie Cooper, thank you for being the best mentor a girl could ask for.

Nikki Greenleaf Berejkoff, my other-half since 1997. I'd be nowhere without you. Thanks for always listening to me and staying my friend this long.

Rachel Opitz. You got me through France. Thanks for helping me through all the madness. Sarah-Louise Raillard, thank you so much for making sure the French portions of my thesis are not a disaster (and if anyone needs editing or translation help, really, she is amazing). And thank you for being such a great friend.

Zoran, Paolo, Elise, Nicolas, Nicolas, Ruth, Ines… mes collègues Français, mes amis de Besançon. Vous tout me manquent terriblement. J'espère qu'on se passera encore.

My great archaeology friends from Colorado who continue to be my great colleagues… Julia Clark and Hannah Chazin. Thanks for supporting me along this path. And Camilla Kelsoe, and Elissa Bullion, who I met a little later, but are archaeology sisters and such supports. And thanks to Bayaraa, Oldzi, Evan, Bruce, Nick, Adam, Alex, Paul… all my Soyo friends. Thank you for giving me the best last season as a Ph.D. candidate.

The simcomp team, Iza Romanowska and Ben Davies… I love you guys and am so glad we are working together on so much.

Philip Verhagen and the Sheep… how have we not known each other for years? Thank you for visiting every David Lynch-ian establishment the Continent has to offer. I'm so glad for your friendship. And to Matt Castle, who I've now known 11 years, who I met in a hostel, and now we do overlapping research. Funny how things work out. Thanks for being a steady support.

And now it's like the Oscars and I'm running out of space, so a list of so many names… too many to count… Scott Ortman, Mark Varien, Simon DeDeo, Tom Brughmans, Phil Riris, Jordan Jarrett, Colin Wren, Denton Cockburn, Ben Bellorado, Donna Glowacki, Caity Placek, Fernando Villanea, Lewis Borck, Jen Dunne, Spencer Wood, Andy Dugmore, Navid Dianati, Matt Grove, Matt Bandy, Caryn Berg, Mitch Allen, Jeremy Van Cleve, Caitlin Wichlacz, Paul Hooper, Bradi Heaberlin, Susan Ryan, Ian Moffat, Neesha Zolinger, Nancy Bertenshaw, Tiffany Wood, Jordan Pearlstein, Brooke Bohnet, Kateri Dodds, Nicole Marie, Sheryl Miller, Susan Seizer… To all of you, and many, many more, thank you.

Nate, my brother, and coauthor in a paper! You're an amazingly talented guy. I'm so proud of you. As I said in my B.A. thesis in 2004(!) you will always be my hero… it's still true. Laura, my big sis, thank you for all your love through the years. Mom, thank you for all of your support through this wild ride. I still can't imagine going back to get an M.A. as an adult with three kids… And Bob. So glad you met my mom.

Gramma Crabtree, who continues to inspire me. Uncle Jim, who saved my bacon helping me register in France. Peter, Sally, Tony, Wendy… the best cousins.

Of course, to my amazing dad, Tom Crabtree, who has helped me through too much to count. The songbirds are singing like they know the score…

Thank you to everyone. I'm so relieved to be done.

TRADE, TERRITORIALITY, ALLIANCES AND CONFLICT : COMPLEXITY SCIENCE APPROACHES TO THE ARCHAEOLOGICAL RECORD OF THE U.S. SOUTHWEST WITH A CASE STUDY FROM LANGUEDOC, FRANCE

ECHANGES, TERRITORIALITÉ, ALLIANCE ET CONFLIT : APPROCHE PAR LES SCIENCES DE LA COMPLEXITÉ DES DONNÉES ARCHÉOLOGIQUES DU SUD-OUEST DES ETATS-UNIS ET D'UNE ÉTUDE DE CAS EN LANGUEDOC (FRANCE)

Abstract

This project utilizes network analysis and agent-based modeling to examine long-standing questions that can only now be asked with the rich data provided in southwestern Colorado and southern France: how Gauls and colonists established economic partnerships, how violence may have shaped the development of multiple levels of leadership, and how early farmers interacted with their environments. Writing a dissertation composed of three distinct case studies, two from the U.S. Southwest and one from the south of France, I use tools developed in complexity science to better address how people in the past dealt with challenges related to resource acquisition. Agent-based modeling and network analysis (both social network analysis and trophic network analysis) will allow me to characterize human decision-making processes and discuss how sharing of strategies within a group can lead to greater fitness of those in the in-group.

Abstrait

Ce projet utilise l'analyse de réseaux et la modélisation à base d'agents pour examiner des sujets classiquement traités mais qui peuvent maintenant être abordés, grâce aux riches données rencontrées dans le sud-ouest du Colorado et en France méridionale : comment les Gaules et les marchands méditerranéens établissaient leurs partenariats économiques, comment la violence a pu façonner le développement de niveaux divers de leadership, et comment les premiers agriculteurs interagissaient avec leur environnement. Pour écrire cette thèse composée de trois études de cas différents, deux dans le Sud-Ouest des États-Unis et un en France méridionale, nous utilisons des outils élaborés par les sciences de la complexité pour mieux aborder comment les individus de la préhistoire surmontaient les défis liés à l'acquisition de ressources. La modélisation à base d'agents et l'analyse de réseaux (sociaux et trophiques) nous permettront de décrire les processus décisionnels et d'analyser comment le partage de stratégies au sein du groupe peut entraîner une plus grande aptitude des individus à agir au sein du groupe.

by Stefani Allison Crabtree, Ph.D.
Washington State University &
Université de Franche-Comté

Co-chairs: Timothy A. Kohler & François Favory

TABLE OF CONTENTS

Abstract ... **vii**

LIST OF FIGURES ... **xi**

PREFACE ... **1**

PRÉFACE ... **2**

CHAPTER 1: INTRODUCTION ... **4**

A Complexity Science Approach ... 7
Complex Systems Approaches to Prehistory: The Example of Hierarchy ... 10
Model Building ... 17
Networks ... 18
Finding the invisible through complex adaptive systems approaches ... 23

CHAPITRE 2 : INTRODUCTION ... **25**

L'approche des sciences de la complexité ... 29
Une approche systémique complexe à la préhistoire : l'exemple de la hiérarchie ... 32
La construction de modèles ... 42
Les réseaux ... 44
Trouver l'invisible grâce aux approches systémiques complexes ... 49

CHAPTER 3: A SIMPLE SIMULATION OF SOUTHERN FRANCE ... **52**

Simulating Littoral Trade: Modeling the trade of wine in the Bronze to Iron Age transition in Southern France ... 56
1. Introduction ... 57
2. Results ... 70
3. Discussion ... 82
4. Future Directions ... 88
5. Conclusions ... 90

CHAPTER 4: AN EXAMINATION OF THE FORMATION OF POLITIES AMONG ANCESTRAL PUEBLOS ... **92**

How to Make a Polity (in the central Mesa Verde region) ... 94
Nestedness, Hierarchy, Log-normality and Power Laws ... 99
Scaling Relationships in Archaeological Data ... 106
Analysis of Kiva Size Distributions ... 113
Analysis of Settlement Population Distributions ... 116
The Model ... 118
Simulation Results ... 121
Discussion ... 126
Conclusions ... 133

CHAPTER 5: A COMPLEX ANALYSIS OF ANCESTRAL PUEBLO FOOD WEBS ... **137**

Cascading Effects and Social Consequences: Food webs in the Ancestral Pueblo Southwest ... 140
Introduction ... 141
Materials and Methods ... 149
Results ... 154
Discussion ... 168

Conclusions 174
Future Food webs studies 176

CHAPTER 6: CONCLUSIONS 179

Lessons from these studies 181

Supplementary Text for Chapter Three: ODD protocol 187

Supplemental Text for Chapter Four 197

Detecting Outliers in Kiva Size Distributions 197
Model: The Public Goods Game 197
Model: Parameter Selection, Group Formation and Territoriality 198
Model: Conflict, Merging, and Tribute 200
Model: Revolt in Complex Groups 202
Model: Fission of Simple Groups 203

Supplemental Tables for Chapter Four 205

Supplemental Figures for Chapter Four 208

Supplemental Tables for Chapter Five 217

References 218

LIST OF TABLES

Table 3.1. How storage level affects the number of individuals in a household and their consumption rates. 66

Table 3.2. Fixed parameters used in this simulation. 67

Table 3.3. Parameters swept across in two models. 68

Table 3.4. Preference Values swept across in this study. 74

Table 4.1. Summary of conformity of kiva-size distributions to power-law expectations.. 114

Table 4.2. Summary of degree of conformity of VEPIIN settlement-size distributions to power-law expectations. .117

Table 4.3. Parameters varied in the runs of the simulation reported here. 120

Table 4.4. Summary of conformity of simulation territory-size distributions to power-law expectations, evaluated in the last year of each of the empirically derived periods. 125

Table 4.5. Summary of analysis results for empirical and simulated distributions. 127

Table 5.1. Periods and Sites examined here. 147

Table 5.2. Scores for human trophic level, generality, vulnerability, connectivity and clustering coefficient by foodweb. 159

Table 5.3. Vulnerability and generality scores of primary prey for humans.. 159

Table 5.4. Generality scores for both empirical data and the reduced foodweb, where only the most important species to Pueblo diet were included. 168

Table S.1. Preference Values swept across in this study. 187

Table S.2. How storage level affects the number of individuals in a household and their consumption rates. 189

LIST OF FIGURES

Figure 3.1. Curves of artifact percentages through time.. 58

Figure 3.2. Area of interest for this study. 62

Figure 3.3. Population response in the simulation, tied to the consumption of grain (grey lines). 72

Figure 3.4. Response of population and artifact type based on preference value 76

Figure 3.5. Response of population and artifact type based on preference value 79

Figure 4.1. Location of the VEP I study area . 98

Figure 5.1. Central Mesa Verde area. 146

Figure 5.2. Graph of overall foodweb. 157

Figure 5.3. Vulnerability measures of species to predation. 158

Figure 5.4. Primary prey of humans, leporids (cottontail and jackrabbit), deer and turkey 161

Figure 5.5. Ideal Clustering Coefficients. 162

Figure 5.6. Clustering coefficient for the overall foodweb. 162

Figure 5.7. Connectivity measures.. 163

Figure 5.8. Human specific foodweb for Grass Mesa Pueblo. 164

Figure 5.9. Human Specific Foodweb, Albert Porter Pueblo. 165

Figure 5.10. Human Specific Foodweb, Sand Canyon Pueblo 166

To **Elena Rose**,
who, in 1998, told me to be an archaeologist
after catching me trying to discover the purpose
of obscure kitchen implements
in that fancy shop downtown.
I listened.
(But I still don't know what those gadgets do.)

PREFACE

This is not a traditional dissertation for two reasons. First, it is composed of three academic papers that have been submitted for publication to three international peer-reviewed journals. These papers advance our understanding of complex adaptive science approaches in archaeology, and how individual decisions can lead to overarching patterns. Each paper builds on the last by adding complexity and realism to the system studied, moving from a simplified theoretical agent-based model of trade in southern France (Chapter 3), to a more complex model of the development of hierarchy among the Ancestral Pueblos (Chapter 4), to a realistic analysis of food webs among the Ancestral Pueblo (Chapter 5). Each chapter begins with a short introduction before moving on to the published or submitted paper.

Second, this dissertation fulfills requirements for a *cotutelle* Ph.D. at Washington State University and the Université de Franche-Comté. As such, this dissertation also incorporates a summary of the work in French, presented as Chapter 2.

I start this work with reflections on the theme of *absence.* I suggest that archaeologists have long desired to understand human relationships in the past, but that these relationships do not preserve, and so we are left studying material culture and not the people who created it. I then move to suggest that complex adaptive systems approaches can help us understand these invisible relationships. I suggest a way forward with archaeological studies, describing the three unique projects I pursued for my double-doctoral studies that utilize complex adaptive systems approaches to understand the archaeological past. It is my sincere hope that this dissertation offers a way forward in methodological and theoretical approaches to studying the past.

PRÉFACE

Ceci n'est pas une thèse de doctorat tout à fait typique. Tout d'abord, elle est composée de trois articles académiques qui ont été soumis pour publication à trois revues internationales à comités de lecture. Ces travaux explorent l'utilisation de démarches de recherche à base de systèmes complexes adaptatifs en archéologie, et nous aident à comprendre comment les décisions individuelles peuvent influencer le développement de configurations globales. Chaque article continue dans le prolongement du précédent, ajoutant complexité et réalisme au système étudié. L'on passe d'une simple simulation multi-agents théorique des échanges en France méridionale (chapitre 3), à un modèle plus nuancé du développement de la hiérarchie des sociétés Pueblos amérindiennes (chapitre 4), pour finir par une analyse réaliste des réseaux trophiques chez les Pueblos (chapitre 5). Chaque chapitre commence par une brève introduction avant de présenter l'article soumis ou publié.

En outre, cette thèse répond aux exigences d'un doctorat (Ph.D.) en cotutelle entre Washington State University et l'Université de Franche-Comté. Ainsi, elle comprend également le résumé de la recherche en français présenté ci-dessous.

Mon travail est introduit par un réflexion sur le thème de l'absence. Les archéologues ont longtemps cherché à comprendre les rapports humains dans les sociétés préhistoriques; malheureusement, ces relations ne se préservent pas, et nous devons souvent nous satisfaire de l'étude d'une culture matérielle et non pas des hommes eux-même. Je suggère donc les approches systémiques complexes peuvent nous aider à comprendre ces rapports invisibles. Les trois projets menés dans le contexte de ce doctorat en cotutelle utilisent des démarches à base de systèmes complexes adaptatifs afin d'éclairer nos compréhensions de processus et de proposer ainsi une nouvelle piste pour la recherche archéologique. Nous avons le ferme espoir que cette thèse contribuera au progrès méthodologique et théorique de cette discipline.

CHAPTER 1: INTRODUCTION

Studying the relationships among people in prehistory is difficult with traditional methods. Especially for the depth of human history where there are no written records, relationships seem to be inexistent, or at least invisible. Yet these invisible relationships are crucially important for understanding how people in the past interacted with each other, and how they chose to make the material culture we find in the archaeological record. Is it possible to go from analyzing things that are present, like potsherds, to things that are absent, like relationships? If we cannot find a record of relationships, are relationships in fact absent?

Archaeology as anthropology of the past (Willey and Phillips 1958:2) has made great advances in understanding the lives of people in pre- and proto-history. While many early studies focused on material culture by necessity (Strong 1935), social-evolutionary narratives (e.g. White 1949; Steward 1955), processual archaeology (e.g., Binford 1965; Flannery 1976) and post-processual archaeology (e.g., Shanks and Tilley 1991) each moved the discipline further toward an understanding of the uniqueness of human lives in the past. Recent approaches have incorporated more nuanced studies of how human actions create the social structures that bound them (e.g., Hegmon 2008; Varien 1999). My dissertation builds on these works, and further explores the ways that human actions and interactions create larger social structures through three case studies. For this work I apply theory and methods developed in complex adaptive systems/complexity science which provide a means to understand human interaction.

The common threads connecting my dissertation are both theoretical and methodological. Methodologically, each of these cases incorporates complex adaptive systems approaches, explained in more depth below. Theoretically, these studies are linked by the concept that individual decisions can lead to greater, system-wide properties. In each of the three studies these changes are seen over time and are often manifest as unintended consequences of years of smaller strategic shifts In this way I address the point by Hegmon (2008:219) that "structural changes… primarily occur at the multigenerational level" and that the agency of individuals "including, but not limited to, new forms of individual actions in the short term—[can] (or [can] not) result in long-term changes." This dissertation thus explores how small decisions can compound over time and lead to changes, and in some cases also explores when changes do not occur (which equally deserve to be explained).

The studies are arranged according to increasing complexity and realism. Chapter two presents this introduction in French. In chapter three I present a simple, theoretical agent-based model examining the trade of wine in Southern France. During the Iron Age in Southern France Etruscan merchants arrived via the Mediterranean Sea and rapidly established trade relationships with the native Gauls, in some cases even settling in townships along the littoral between 600 and 500 B.C. (Py 2012). During this time they traded wine with the native Gauls and established extensive economic partnerships within the region. After 500 B.C. Greek wine arrived, quickly replacing Etruscan wine. Gauthier et al. (2008) modeled the distribution of multiple types of resources (bronze, flint, jadeite, salt, millstones, axes, weapons, tools) across Europe to examine how the production, supply, and diffusion of these objects changed through time, and how these products related to the establishment of exchange hubs. Their work shows the utility of mapping the presence of different products across Europe, and how the movement of these goods would create a vast network of trade. While their study has a longer temporal lens than the one presented in chapter three, the lessons from Gauthier et al. (2008) are taken to heart: we need to understand the presence of specific types of goods and their distribution across space to understand the development of early economies. I specifically examine households toward the top of the hierarchy, since wine is a luxury good that was not readily available to the entire populace, though the less wealthy farmers may have been critical for the production of surplus to enable trade for wine. The paper presented in chapter three explores the local reasons that (wealthy) individuals would choose to switch their drinking habits, encapsulated by preference for one type of wine over another. When one object has a monopoly on the industry, its rapid replacement deserves explanation.

In chapter four I examine the development of hierarchy among the Ancestral Pueblo Southwest and suggest that agent-based modeling can help with our understanding of the development of social structures in prehistory. In this research I build upon Kohler et al.'s (2012) model of hierarchical development (itself an expansion of Hooper *et al.*'s [2010] model), as well as Kohler *et al.*'s (submitted) model to examine how the threat of conflict can lead toward hierarchical societies, and determine if the hierarchical structure emerging in this iteration of "Village" resembles the archaeological record. To compare this model with the archaeological record, I specifically examine the size of settlements and kivas through time, comparing the distributions of the sizes of each of these archaeological datasets to lognormal and power-law distributions, arguing that power-law distributions express a tendency toward hierarchy. Kiva size roughly corresponds to the size of the groups that used them, and kivas are generally measured accurately by archaeologists of different projects. However across the Southwest, site size has been measured differently by archaeologists in various projects, thus augmenting that data with kiva data increases our understanding of the hierarchical organization of groups. By comparing the distributions of site sizes and kiva sizes against the distributions of group sizes in the simulation I am able to examine how and when hierarchies form. In this way I explicitly examine how group formation influenced settlement size and the development of hierarchy in the prehistoric record.

In chapter five, I examine the dramatic ecosystem shift of the central Mesa Verde region during its 700-year occupation by Ancestral Pueblo people. Here I use the archaeological record in combination with modern ecological data to examine food webs in the past. For the past century archaeologists have been asking why the Ancestral Pueblo people left the northern Southwest so swiftly and completely in the A.D. 1200s. Reasons for the abandonment have rested on both environmental and social causes, or more recently a combination of the two. In chapter five I examine key prey species in archaeological assemblages, and argue that changing species composition had cascading effects on the environment, as well as how environmental changes influenced species composition. I show that this, coupled with natural climatic fluctuations and anthropogenic environmental change increasingly made the Four Corners area of the U.S. Southwest less productive for farming and wild-game procurement. Increasing aridification through the disappearance and appearance of four key species is apparent. I argue that while human omnivory provided some resilience to environmental change, a decrease in key prey likely contributed to decisions to leave the Four Corners area.

Each of these studies aims to understand how the actions and interactions of individuals could lead to the overall patterns observed in the archaeological record, whether that is the development of a complex economic system, the growth of hierarchy, or the modification and change of the environment. Complexity science approaches help to clarify how the decisions of individuals can lead to system-wide changes, thus building on the research of multiple other scholars who have sought to understand the lives of people in prehistory.

A Complexity Science Approach

Melanie Mitchell, a computer scientist, recently defined a complex system as “a system in which large networks of components with no central control and simple rules of operation give rise to complex collective behavior, sophisticated information processing, and adaptation via learning or evolution” (2009:13). Further, complex adaptive systems are present when “things relate but don’t add up, if events occur but not within the processes of linear time, and if phenomena share a space but cannot be mapped in terms of a single set of three-dimensional coordinates” (Mol and Law 2002:1). When these statements are true, the system being studied is likely a complex system, and approaches from complex systems, such as network analysis or agent-based modeling, may help in its examination.

Complexity approaches allow us the possibility of examining how higher-level structures (such as groups) emerge from individual interactions (such as interpersonal relationships). In this way complexity is a perfect vessel for navigating the choppy waters of archaeology. These themes have been explored by Bentley and Maschner (2008) and Kohler (2012), and by Bocinsky (2014) who demonstrated the utility of complexity studies for archaeological data and builds on these foundational works.

The theoretical underpinnings of complexity science as applied to archaeology can be stated in a few precepts:

1. individuals matter, so we need to study the actions and interactions of individuals;
2. system-wide behaviors cannot simply be understood via the summing of individual parts, but when individuals interact together they create larger systems;
3. system behaviors typically include non-linearities;
4. change and adaptation are typical of complex systems, yet maladaptive behaviors may survive and even proliferate under certain circumstances.

In a classic example of how complex systems function, Reynolds (1987) showed that when individual birds create complex murmurations by following just three simple rules: 1. Retaining alignment with the flock; 2. Steering toward the average of the neighbors' headings; and, 3. Maintaining adequate space between oneself and one's neighbors. When individual birds follow these rules, the flock becomes a complex, moving system, able to respond to exogenous effects (such as the presence of obstacles or being attacked by a predator, which likely have their own rules) in ways that would not be predicted by looking at the individual strategies alone. Complexity science in this way can help researchers understand nuances that may otherwise be obscured by larger group processes or provide candidate mechanisms for the emergence of group structure at larger scales.

Complexity theory thus provides a way to see not just individual behaviors (the choices of individual birds) or system behaviors (the movement of the flock), but how individuals influence one another and how individual behaviors affect system-wide behaviors. Complexity theory tells us that we must pay attention to how individuals connect to one another via networks, and to understand the properties of the networks we must examine how information or goods flow among individuals. Small changes in how individuals interact can have dramatic effects on the system, but we cannot understand the system merely via the summation of its parts.

We know, however, that humans are infinitely more complex than birds. If we take the example mentioned above of the pot traded across 200 km, we may expect that one or more individuals traded that pot across the landscape; thus we can potentially see the interaction of two or more individuals linked together though the movement of a pot. Moreover, we may be able to understand that transaction via a complex systems approach, since trade was likely not limited to one ceramic vessel. Here, if we looked at the suite of traded pots we may be able to connect them via a social network, suggesting that people at the source of the ceramic material traded with those at the source of the finished pot, creating a link between these two communities. Thus complexity science, and network theory specifically, enables us to see the individual ceramic maker (and ceramic buyer) as well as the overarching trade network that links many actors together in a complex interconnected sphere.

The theoretical platform of complexity science—that individual decisions matter, that these decisions will have cascading effects on the system, and that individuals and groups will change and adapt—can provide a novel approach for examining the archaeological record. We can examine the individual, the family, the group, and the overarching structure, all by applying a simple suite of rules.

Complex Systems Approaches to Prehistory: The Example of Hierarchy

One hundred years apart, two philosophers weighed in on the idea of humanity's innate nature in terms of individuality or collectivism. Hobbes (1651) suggested that humans are inherently competitive. Exactly 100 years later, Rousseau (1751) had a rosier outlook on humanity, suggesting that humans can group into cooperative collectives for mutual benefit.

Multilevel selection provides one way to examine both low-level and higher-level processes (Richerson and Boyd 2005; Turchin 2003; Turchin and Gavrilets 2009; Wilson 2002). Multilevel selection is conceptualized by D. S. Wilson and E. O. Wilson (2008) as a nested selection process (which they compare to Russian Matryoshka Dolls); classic evolutionary selection will act on the individual (the smallest doll), but contrasting selection measures may act on the group (or groups of groups; the larger doll/dolls) thus providing a "nested" selection process. Multilevel selection provides a means for understanding how conflicting processes such as altruism and competition could each play key roles in society.

In this way, we do not need to choose between Hobbes and Rousseau to understand how humans cooperate or compete. Cooperation and competition are not mutually exclusive. There will be differing scales at which competition or cooperation work for the benefit of the individual and the group (Carballo et al. 2014).

Traditional archaeological analyses of hierarchy focus on either "top-down" approaches (*sensu* Brumfield and Earle 1987; Earle 1987; Service 1962), or "bottom-up" approaches (*sensu* Fried 1967, discussed in Pauketat 2007:22). While these approaches help to describe how hierarchy exists in a final state, these approaches do not adequately help us understand the development of hierarchy.

The spread of altruism in a group depends on a balance between individual-level and higher-level selection forces (Turchin and Gavrilets 2009: 169). "Human groups need to be well-integrated by within-group cooperation in order to effectively compete against other groups" (Turchin and Gavrilets 2009: 169). Competition between internally cooperative groups is a common method of instantiating multi-level selection, illustrating how selective forces on individuals may contrast with selective forces on groups.

The trade-offs between individual- and group-level benefits are explored by Hooper et al. (2010). In their mathematical model, groups play a repeated public goods game following a framework developed by McElreath and Boyd (2007). Individuals in a large population are randomly grouped together, and individuals contribute to a public good. Contributing to the public good costs each individual, but the end benefit is greater than the costs to everyone individually, and output is shared equally among all members of the group. Because the end benefit is evenly divided regardless of contribution, there is a temptation to defect by certain members, as individuals carry various traits related to cooperation. Consequently, groups may either elect to pay a leader via taxation to monitor and punish defection, or non-elected (and unpaid) "mutual monitors" attempt to monitor defection. For both leaders of hierarchical groups and mutual monitors, punishment comes at a cost to the punisher. Mutual monitors do well when everyone in the group cooperates and plays the public goods game, but as group size increases the likelihood of defection also increases, and the strain on mutual monitors increases as well. Inversely, hierarchical groups do less well than mutual monitors when groups are small, but as groups grow in size it becomes advantageous to pay a leader to devote all of its time to monitoring the group members to ensure there is no defection. There are stabilizing dynamics for the number of cooperators to defectors, and the choice to use mutual monitors or paid leaders; in this model, as group size increases, hierarchical groups do better because mutual monitors do so poorly in large groups that only a full-time leader provides protection against, and punishment for, defection. This paper thus directly examines why individuals would choose hierarchy—to quell defection and increase in-group cooperation—and the under-appreciated relationship of that choice to group size.

Kohler et al. (2012) instantiated a more detailed version of Hooper et al.'s model in the semi-realistic agent-based setting provided by the "Village" model (Kohler and Varien 2012). In their implementation, non-hierarchical and hierarchical groups each play public goods games within their groups, which were non-territorial; in this model the public goods game was paid via maize, but since the model corresponds to the Ancestral Pueblo Southwest it is assumed to represent a real public good, such as a wall or a reservoir. In this model, individuals in hierarchical groups performed better than non-hierarchical individuals did as group size increased, with the result that hierarchical groups proliferated. This is due to the ability of hierarchical groups to support leaders to monitor and punish defection, showing the benefit of hierarchy and how hierarchy may have developed as individuals engaged in cooperative projects.

In this way, Hooper et al. (2010) and Kohler et al. (2012) address the difficult issue of why individuals would give up their autonomy and join groups: this is explained by the higher rewards from individual effort when matched with those of others in a successful public goods game. Their work helps explain why individuals would join groups, and even submit to the wishes of a leader, providing the basis for understanding development of hierarchy. However, in the Kohler et al. model, the only hierarchy present was within groups (regular citizens, and leaders who specialize in punishing defectors and collecting taxes). To understand hierarchies *of* groups, other methods are needed. Work in defining the organizational characteristics of cities can help us understand hierarchy on this scale.

Pumain (2006: 179) suggests that we cannot infer the importance of a city based merely on its size, and indeed computing the size of a city is complicated. (Do we assume the area, or the population, dictates size?) Instead, we need to understand a city's importance in its relation to other communities. Unfortunately, in archaeology most of what we have to work with is standing (or once-standing) architecture. Our approach in chapter four utilizes the size of sites to infer a hierarchy, but supplements those data with data on the size of the ritual and domestic spaces referred to as kivas, as well as a simulation that builds hierarchy from the ground up. In this way we address possible concerns by looking at hierarchy in not only populations of settlements, but sizes of ritual spaces, and sizes of polities developing through time.

In recent work, Bettencourt (2013) has found that infrastructure of cities follows increasing economies of scale. That is, as cities grow, the amount of infrastructure needed does not increase linearly with size, but increases sublinearly, while the social benefits of living in cities increase faster than does city size, comparing across cities of varying size. Building on this work, Ortman et al. (2014: 2) state that "this accumulation of functions with population size also provides a mechanism for the genesis of settlement-size hierarchies that characterize both ancient and modern societies."

Pumain observes (2006:174) that "unlike villages (or mining settlements) that exploit resources at their *site,* or in close their close neighbourhood, towns and cities make a living from the wealth created by their *situation*." This 'situation' that Pumain speaks of is the importance that aggregated settlements accrue based on accelerating social capital due to the density of interactions that cities provide.

Ortman et al. (2014) show that archaeological settlements in the Basin of Mexico follow urban scaling properties similar to those of modern cities. The organizational properties of the prehistoric cities show similar increasing economies of scale, and likely reflect a political hierarchy due to the challenges of organizing a large population effectively (though see Froese *et al.* 2014 for a view of Tenochtitlan as organized without hierarchy).

But how do we move from individuals in groups playing for positive returns in a public goods game in the Hooper et al. (2010) and Kohler et al. (2012) models, to the growth of large settlements and cities that Bettencourt and Ortman and colleagues examine? Here, work on conflict, specifically conflict *between* groups, can be instructive and can help us learn how hierarchical societies have developed.

Conflict, and even the threat of conflict, are driving forces for societal development (Turchin and Gavrilets 2009). Turchin and Gavrilets (2009: 170) note that warfare drives human groups to greater internal cohesion, increasing technological advances, and can help drive increasing group size. The development of hierarchies in their estimation is based on the desire to avoid, or win, in conflict.

> The growth of hierarchically organized societies occurs by chiefly villages adding subordinate villages and by adding new layers of hierarchy on top

> of the pre-existing ones. Thus, hierarchical societies … can potentially reach any size (Turchin and Gavrilets 2009: 171).

Turchin and Gavrilets (2009: 172) also suggest that if the development of hierarchy is a natural process, hierarchies "should reflect this evolutionary history, just like biological organisms retain many traces of their evolutionary history." They go on to state: "all human societies, even the simplest ones (and in stark contrast to large-scale societies of social insects), are organized hierarchically" (Turchin and Gavrilets 2009: 172). This is true even in groups that self-organize; individuals group into families, and families group into lineages or villages. This nested structure can be seen as an inherent hierarchy, and we can use this self-similar organization to understand past societies.

As evidenced by the study by Ortman et al. (2014), complexity science is a perfect pairing with the large, rich datasets that many archaeological projects provide. Recent efforts have been able to synthesize large areas and deep datasets, making use of historic and archaeological research as well as the vast amounts of data these projects provide (Bettencourt 2013; Klingenstein et al. 2014; Kohler and Reese 2014; Mills et al. 2013; Ortman et al. 2014; Schwindt et al. 2015).

While complexity science can delve into different types of questions than traditional archaeological studies, the studies presented in this thesis, which employ complexity science, are built on more than a century of traditional archaeological research. Key foundational studies include Alfred V. Kidder's (1924) synthesis, driving studies in Southwestern archaeology towards chronological coherence; his chronology is still used to discuss Pueblo archaeology. More than half a century later, work by the Dolores Archaeological Project (Breternitz et al. 1986) advanced research on Pueblo habitation, especially late Basketmaker and Pueblo I archaeology. Recent efforts have built on these, attempting to understand hierarchization processes in the past, advancing understanding of how social structure can be read off of size and placement of structures (Kohler and Higgins 2016; Schachner 2001, 2010; Ware 2014). In Southern France, the understanding of the archaeology of Bronze and Iron Age societies relies on the foundational work of Michel Py (1990, 2012), whose ability to understand, track, and synthesize the prehistory of the area brings to mind the work of V. Gordon Childe (1936). Building on Py's work, Dietler (e.g., 1990, 2010) places southern Gaul in a greater web of interaction with the known world of antiquity.

What is clear from the above discussion is that complex adaptive systems approaches articulate well with trying to understand how hierarchy develops. Yet the study of the development of hierarchy would be impossible without being able to explore the actions and interactions of individuals. Individuals interact together, and to avoid defection of group members, they employ a leader to help manage public goods projects. This, then, can lead to growth in hierarchy. Thus we can look at the individual and agency, or the group and structure, both under the umbrella of the same study.

Hierarchy is also evident in the Gaulish case, although by the Iron Age period examined in this dissertation, it had already been well established. In analyzing the trade of grain for wine, I implicitly examine how a luxury good (wine) influences the production of surplus (grain) which disproportionately benefited the elite. Wine was not a good available to the common populace, but instead is found exclusively in elite contexts (homes, burials). Wine was important for the symbolic reinforcement of hierarchy, and so analyzing the displacement of one type of luxury good for another helps in the study of Gaulish hierarchy. Thus, a model-building approach helps to understand how the trade in luxury goods influenced the development and maintenance of Gaulish hierarchy. While decades of research have focused on cross-cultural studies of human systems from an often-inductive point of view, model building and theory testing provide a novel way to examine the world, helping to answer questions that would be unanswerable from traditional approaches (Lake 2014).

Model Building

A model is an idealized microcosm of a real system and is built on theory, or, as Clarke (1972: 2) states "models are pieces of machinery that relate observations to theoretical ideas." Even models built on simple rules can help eliminate poor hypotheses, clarifying understanding of a system. Even when a model is wrong (as "all models are wrong, but some are useful" [Box and Draper 1983: 424]) we can glean a better understanding of the system by slowly building the model up and studying simplified processes of complex systems.

So, what is agent-based modeling? Most obviously, agent-based modeling is a computer simulation tool, but it is first a tool to understand intractable behaviors. Agent-based modeling is useful in understanding how aggregate records or behaviors emerge from individual decisions. Such behaviors do not lend to simple formalism such as a set of differential equations which can only represent slowly changing states with fidelity. In agent-based modeling the agents are the individuals that we want to study, be they cells, individual people, families, even cities. We imbue the agents with rules on how to behave in certain situations, and those agents act on those rules through simulated time in a virtual environment. We output the interactions, and where possible compare patterns created by the agents with those visible in an archaeological record.

Costopoulos, Lake and Gupta tell us that:

> Simulations can surprise us. Whether the surprises are due to our faulty understanding of the reality we are modeling or to our faulty modeling of the reality we are seeking to understand, they can force us to reexamine our assumptions and to push beyond the intuitive models of the past for which we often settle too easily (Costopoulos et al. 2010: 2).

Thus simulations help us examine the theories we have developed about the world and craft better models to describe the world. In this way there is feedback between the tools of complexity science (simulation) and the theory itself. Simulation and complexity science force us to reexamine how we see the world. Simulation enables us to test theories developed by anthropologists and historians from years of cross-cultural research (Lake 2014: 699). Simulation can address different questions than cross-cultural research can, and can easily help refine hypotheses of the archaeological record.

Agent-based modeling developed in conjunction with the development of complex adaptive systems research and enables the direct examination of both individuals and collectives of individuals or structures; the early agent-based modeling platform "Swarm" was developed in the mid-1990s at the Santa Fe Institute, itself one of the leading institutions studying complex adaptive systems (Kohler and Gumerman 2000). In this dissertation the complex adaptive systems tools of agent-based modeling and network analysis are used to understand the prehistory of the American Southwest and Southern France. Together they help understand the relationships among individual decisions and behaviors and group structure.

Networks

But, why networks? As argued by Carl Knappett (2011: 10), and discussed in Brughmans (2012: 3):

> 1. [Networks] force us to consider relations between entities; 2. They are inherently spatial, with the flexibility to be both social and physical; 3. Networks are a strong method for articulating scales; 4. Networks can incorporate both people and objects; 5. More recent network analysis incorporates a temporal dimension (Knappett 2011: 10).

According to Knappett (2011), networks provide a way for us to conceptualize entities as well as their links in space and through time, which provides methodological advantages due to the complex structure of networks. Network studies vary widely with respect to their reference systems, ranging from the study of social interactions, to the study of how species interact in a foodweb, and far beyond (Evans and Felder 2014). The key similarity in all forms of network studies, though, is the idea that the relationships between entities matter as much as the entities themselves do (Brughmans 2012).

Network analysis is undergoing an intensification in the social sciences. In the media we are familiar with social network analysis via, for example, Facebook interactions (Backstrom and Kleinberg 2013) but network-based studies are increasing in anthropology (see, e.g., Evans and Felder 2014). While network approaches have been used since at least the 1950s and 1960s (Epstein 1969; Erdős and Renyi 1959; Erdős and Renyi 1960; Erdős and Renyi 1961), modern approaches are able to use large datasets to understand not only how individuals interact with each other, but also how the system changes with changing interpersonal interactions.

Here I will use the term "network" to mean a graph with nodes and links (Brughmans 2012). Nodes are the actors in the network, whether they are individuals, groups of individuals, or even species. Links (or ties) specify which nodes interact, and how; the term "edges" usually refers to undirected links, whereas "arcs" usually refers to directed links (Hanneman and Riddle 2005; Wasserman and Faust 1994). Differentiating between two main approaches in network analysis—Social Network Analysis, or SNA, and Trophic Network Analysis, or food webs—will be important in this dissertation.

Social Network Analysis is concerned with how people are connected (see below), while Trophic Network Analysis is concerned with how producers and consumers are linked in ecosystems via consumption patterns. Brughmans (2012: 10) notes that the beginning of SNA stems from the field of sociometry, developed in the 1930s by Harvard scholars (Moreno 1934, 1946, 1960; Moreno and Jennings 1938). Sociometry aimed to depict interpersonal relationships in two-dimensional space (a graph). Freeman (2004: 30) asserts that sociometry "was the first work that included all of the defining features of social network analysis."

The study of food webs also has deep roots. The earliest graph of a foodweb is attributed to Lorenzo Camareno (1880), with similar work from Shelford (1913), and Summerhayes and Elton (1923; discussed in Egerton 2007). Many decades later, Yodzis and Inness (1992) formalized how producers and consumers relate to one another in trophic networks via relationships between creation of biomass and predation upon biomass. In 1998, Estes et al. created the first foodweb model of nearshore and oceanic systems by looking at the functional response of killer whale predation on sea otters—a study seen as a landmark for modern foodweb approaches.

Links are always directed in trophic network analyses, since one species consumes the other. Although there are instances of reciprocation in which a species will both prey on and be prey to another species (wolves and cougars, for example, might each opportunistically eat each other), the key characteristic of trophic networks is the directionality of the feeding links. Common analyses of trophic networks include removing species to see how resilient the network is to extinction (e.g., Binzer et al. 2011; Brose 2011), examining the effects of diet shifts by key species (e.g., Ramos-Jilberto et al. 2011), examining declines (or increases) in species richness (e.g., Murphy and Romanuk 2014; Romanuk et al. 2009), and examining how different functional types of species, like parasites, affect networks (Dunne et al. 2013).

Social networks, unlike trophic networks, can have directed links (unreciprocated friendships, or donations) or undirected links (reciprocated friendships and gifts). Some of the most commonly used measures in SNA approaches to archaeological data are centrality measures: degree centrality, betweenness centrality and eigenvector centrality (Brughmans 2012: 14). Such measures have been used to argue for the importance of specific sites in migration events (Mills et al. 2013), the evolution of Cahokia as a major political center (Peregrine 1991: 68), or the spread and diffusion of pottery through sites in the Roman World (Brughmans 2010). Centrality measures are useful for archaeology because they reveal which nodes are the most important for the functioning of the network, with implications for the size or the location of sites. Or, reversing the logic, such measures might help explain how or why certain locations became important.

Network science thus acts as a bridge between the local details of the nodes and the overall structure of a system, recalling the discussion above of agent-based modeling which honors both the agency of actors and the structure of the system. Brughmans argues that "it is a combination of SNA and complex network simulation techniques that seems to hold the true potential of networks for archaeology" (Brughmans 2012: 19).

In one recent study that exemplifies the use of social networks in archaeology, Collar (2007) explores religious innovation in the form of the invention of monotheism in the Roman Empire. She examines how religious ideas flowed in the religious network of the cult of Theos Hypsistos, and how Christian orthodoxy came to become dominant. She finds that small-world theory or "innovation cascade" (Collar 2007: 150) helps explain why monotheism so successfully spread in the declining Roman Empire. Collar's work demonstrates how to explore archaeological data with network science, using complexity theory to help us understand how a complex observed phenomenon (the dominance of Christianity) can result from simple actions of key individuals (influential nodes that affect the system).

In another influential study, Mills and colleagues (2013) have used networks to examine the similarity of ceramic design across the U.S. Southwest, arguing that such networks allow archaeologically interesting distinctions such as ethnic boundaries to be mapped onto sites and regions. The strengths of this study lie first in its use of vast amounts of data, and second in its graphic illustration of connectivity in the Southwest, something that is impossible to achieve with verbal models.

Communication networks are also important for understanding prehistory. Garcia (2005: 174) finds that communication and trade networks influenced the locational choices made by Iron Age Gauls made in building their settlements. He moreover identifies four traits necessary for the development of urbanization. These are:

1. agricultural surplus;
2. the establishment of commerce;
3. group cohesion; and
4. the emergence of a political power.

The first two traits are explicitly modeled in the paper presented in chapter three. While Garcia's third trait is somewhat implied in the model, in that agents involved in a trading relationship will preferentially live closer to one another, group cohesion never explicitly solidifies in the model built for this dissertation. Further, the model presented in chapter three does not model the emergence of a political power; rather it treats all agents as autonomous actors without regard to a hierarchical structure. The model presented in chapter four, however, explicitly models the emergence of a political power, while also incorporating the other four traits listed by Garcia (2005). It can be argued that the processes modeled in chapter three, when further developed, would lead to the complex polities that develop in chapter four.

The benefits to archaeology of network approaches include at least that they analyze and display the connectivity among nodes in ways that lend themselves to comparisons among different networks providing intuitively understandable and analytically useful translations of abstract concepts such as centrality, and that they can reveal the vulnerability of systems. One can see exactly how the network responds to removal of nodes, and one can predict how the system would rearrange itself due to external perturbations.

Finding the invisible through complex adaptive systems approaches

I began this chapter by suggesting that it is difficult to understand past human relationships through traditional archaeological methods. The fact that artifacts preserve, but relationships disappear, creates great challenges for the study of ancient humanity.

Complex adaptive systems approaches, however, provide ways to examine relationships among individuals in the past. Through these methods we can directly observe how individuals make decisions (in the case of agent-based modeling) or link to other individuals (in the case of network analysis) and can examine the effects of these actions and interactions on the larger structure. Complex adaptive systems approaches thus help advance archaeological research to study not just the tangible (artifacts) but the intangible and invisible (relationships).

These approaches also enable us to not only examine one scale, but multiple scales of interaction, breaking limitations placed on research in the past. Returning to the centuries-old positions of Hobbes vs. Rousseau—humans are competitive, humans are cooperative—the "right" answer may depend on the scale of analysis. Complex adaptive systems, by allowing us to bridge scales, can help us to understand how individuals, who by definition should be looking out for themselves, nevertheless can find sufficient common interests to group into stable collectives.

Complexity theory helps to unravel the archaeological record. While we can look at modern flocks of birds and understand them from individual behaviors, so, too, can we look to the archaeological record, which by nature is in aggregate, and understand its derivation from individual choices. As Dietler (1990: 381) has said about Bronze to Iron Age France, "cultural change is an unintended result of a combination of decisions and actions by individuals and households experimenting with change, rather than by cultures or societies." Unintentionally, Dietler evokes theory parallel to that of complexity science; it is the choices of individuals that drive societal change. Thus it is my hope that through the research presented here I am able to forge a pathway to examine the people in prehistory, the social structures they created, and the effects these had on the environment as a whole.

CHAPITRE 2 : INTRODUCTION

L'étude des rapports interpersonnels dans les sociétés préhistoriques est difficilement réalisable avec les méthodes classiques de l'archéologie. Pour la vaste majorité de l'histoire humaine pour laquelle il n'existe pas d'histoire écrite, les relations demeurent totalement invisibles. Or ces rapports invisibles sont d'une importance fondamentale pour apprécier la manière dont les personnes interagissaient dans le passé, et ainsi comment elles choisirent de créer la culture matérielle dont nous retrouvons les traces aujourd'hui dans le patrimoine archéologique. Est-il possible de passer de l'analyse d'objets tangibles, tels les tessons, à l'étude d'objets absents, tels les rapports humains ? Si nous n'avons pas accès à la trace écrite de ces rapports, sont-ils effectivement absents ?

L'archéologie, étudié comme l'anthropologie du passé (Willey et Phillips 1958 : 2), a beaucoup fait avancer notre compréhension de la vie des gens de la pre- et protohistoire. Tandis que les premières études ont focalisé par nécessité sur les vestiges matériels (Strong 1935), les schémas socio-évolutionnistes (par exemple, White 1949 ; Steward 1955), l'archéologie processuelle (par example, Binford 1965 ; Flannery 1976), et l'archéologie postmoderniste (post-processualisme) ont fait progresser la discipline vers une compréhension des vies des humains du passé, et pas seulement de leurs objets. Les approches récentes ont intégré les nuances des actions et interactions humains, et comment ces actions ont crée des structures sociales (par example, Hegmon 2008 ; Varien 1999). Ma thèse contribué à ces études et examine en particulier les conséquences des actions humaines la développement des hiérarchies. Pour ce travail, j'ai mobilisé des approches de systémiques complexes pour améliorer ma compréhension du comportement humain. Les approches à base de systèmes complexes adaptatifs, en provenance des sciences de la complexité, nous fournissent un moyen de saisir les rapports humains, et surtout de comprendre comment l'interaction de nombreux individus peut engendrer une forme supérieure à la somme de ses parties.

Les points communs reliant ces trois études de cas sont à la fois théoriques et méthodologiques. Du point de vue méthodologique, chacune de ces études de cas intègre une approche systémique complexe (expliquée plus en détails ci-dessous). Du point de vue théorique, la notion du personne telle que défendue par I. Hodder (1982, 2000), impliquant que les décisions individuelles peuvent avoir des conséquences plus vastes à l'échelle de tout un système. Ainsi, je reprends le point de vue de M. Hegmon (2008 :219), selon lequel « les changements des structures se passe au niveau multigénérationnelle » et selon lequel le libre arbitre des individus «est inclus, mais pas limitée à, des formes nouvelles d'action individuelles pensées à court terme − mais [peuvent] (ou ne [peuvent] pas) être le résultat de changements sur la longue durée. » Cette thèse explore comment les petites décisions peuvent augmenter et conduire aux changements, et aussi dans certains cas explorer lorsque les changements ne s'opère pas.

Ce travail est organisé par étude de cas, en ordre de complexité et de réalisme croissant. Le présent chapitre sert d'introduction en français. Ensuite, dans le chapitre 3, nous présentons un simple modèle théorique de simulation multi-agents qui examine les échanges fondés sur le commerce viticole dans le sud-est de la France. Pendant l'âge du fer (entre 600 et 500 Av. J.-C.), les marchands étrusques arrivèrent en Gaul méridionale par la mer Méditerranée et établirent rapidement des rapports commerciaux avec les Gaulois autochtones, s'installant dans certains cas dans des localités le long du littoral (Py 2012). A cette époque, les marchands vendirent du vin aux Gaulois et développèrent de vastes partenariats économiques à travers la région. Après 500 av. J.-C., le vin grec de Marseille arriva. Le vin étrusque perdit beaucoup de sa popularité et fut remplacé par le vin grec-Marseillaise. Gauthier *et al.* (2008) ont modélisé la distribution de plusieurs types de ressources (du bronze, du silex, de la jadéite, du sel, des meules, des haches, des armes et des outils) à travers l'Europe pour examiner comment la production, l'approvisionnement et la circulation de ces objets a changé avec le temps, et comment ces produits ont affecté l'établissement de centres d'échanges. Leur travaux montre la valeur d'un recensement des produits divers et variés à travers l'Europe, et leur modélisation suggère la manière dont ces produits ont pu créer un vaste réseau commercial. Quoique cette étude ait une perspective temporelle bien plus large que celle du chapitre 3, nous prenons à cœur les leçons de Gauthier *et al.* (2008) : il est essentiel de comprendre la présence de produits particuliers et leur distribution spatiale afin de comprendre le développement d´économies émergentes.

Dans chapitre 3 j'examine les aristocrates gaulois—les individus et maisonnées qui sont au sommet de la hiérarchie de la société gauloise—car le vin n'était pas une denrée populaire accessible au peuple. Néanmoins, les fermiers sont tout de même considérés comme des acteurs certainement importants pour la production du surplus nécessaire pour échanger les biens agricoles contre du vin. Le chapitre 3 explore les raisons locales pour lesquelles les individus ont pu changer d'habitude en matière de consommation de vin. Quand un objet détient le monopole sur toute une production, son remplacement rapide est suspect, l'absence relativement subite du vin étrusque mérite donc d'être analysée.

Au chapitre 4, j'analyse le développement de structures hiérarchiques des sociétés Pueblos du Sud-Ouest des États-Unis et suggère que la simulation multi-agents peut aider à notre compréhension du développement des structures sociales. Nous tirons ainsi parti d'une part du modèle de développement hiérarchique de T. Kohler *et al*. (2012) — qui est lui-même le prolongement du modèle de P. Hooper *et al.* (2010) — d'autre part du modèle (*Submitted*) de T. Kohler *et al.* pour examiner comment la menace de conflit peut contribuer au développement de sociétés hiérarchiques. Il s'agit de déterminer si la structure hiérarchique émergente dans cette version du modèle VEP de « Village » produit des résultats similaires aux observations archéologiques. Pour valider ce modèle par rapport aux données archéologiques, nous examinons en détail la taille des villages et des kivas à travers le temps, en comparant les distributions des données archéologiques par rapport à une distribution lognormale ou par rapport à une loi de puissance, faisant valoir que les distributions en loi de puissance expriment une tendance à la hiérarchie. Ici nous analysons la taille des kivas normales et les « grandes kivas », ainsi que la taille des anciens villages, afin de déterminer si une structure suivant les lois de Horton semble émerger, comparant celle-ci ensuite à la taille du site et du groupe dans la simulation. De manière générale, la taille d'une kiva correspondait *grosso modo* à la taille du groupe qui s'en servait. Quoique les kivas aient souvent été mesurées avec précision par de nombreux archéologues, à travers le Sud-Ouest des États-Unis la taille des sites a souvent été mesurée de façon différente dans le contexte de projets différents. Dans notre simulation, bien que nous ne permettions pas à nos agents de construire des kivas, la comparaison de la taille des kivas différentes autorisée par les données archéologiques nous permet d'identifier quelles simulations (et ainsi quels paramètres) correspondent le mieux aux données pour la taille des villages à travers les époques. Nous pouvons ainsi expliquer comment la formation de groupes influença la taille des villages et le développement de structures hiérarchiques pendant la période préhistorique.

Au chapitre 5, j'examine la transition dramatique de l'écosystème a Mesa Verde pendant les 700 ans d'occupation de quoi ? . Ici nous laissons de côté les simulations multi-agents, associant plutôt les données archéologiques avec certaines données écologiques modernes afin d'explorer d'anciens réseaux trophiques. Au cours du siècle dernier, les archéologues se sont demandé pourquoi les Pueblos quittèrent la région septentrionale du Sud-Ouest américain si rapidement et de façon irréversible aux environs de 1200 ap. J.-C. Leurs justifications sont souvent fondées sur des causes environnementales et sociales, et plus récemment sur une combinaison de ces deux facteurs. Au chapitre 5, nous étudions quelques espèces proies clés trouvées dans les assemblages archéologiques, en s'appuyant sur l'hypothèse que des changements dans la composition des assemblages d'espèces a des effets en cascade sur l'environnement. Des conséquences néfastes, conjuguées aux fluctuations climatiques naturelles et aux changements climatiques d'origine anthropogénique, ont sans doute progressivement transformé la région des Four Corners du Sud-Ouest des États-Unis, réduisant son niveau de productivité agricole et son abondance en gibier. L'aridification progressive du climat se perçoit à travers la disparition et l'apparition de quatre espèces importantes : le wapiti, le lièvre, scaled quail (un type de caille indigène des déserts américain), et la grue du Canada. Bien que la caractère omnivore des humains fournisse une certaine résilience des gens aux changements environnementaux, une diminution importante du nombre d'espèces-proies contribua vraisemblablement à l'exode des groupes humains de la région des Four Corners.

L'approche des sciences de la complexité

L'informaticienne Melanie Mitchell a récemment défini un système complexe adaptifs comme « un système dans lequel de vastes réseaux de composantes sans contrôle central et avec des règles de fonctionnement simples donnent lieu à un comportement collectif complexe, un processus de traitement des données sophistiqué, et un potentiel d'adaptation par l'apprentissage ou l'évolution » (Mitchell 2009 : 13). En outre, les systèmes complexes adaptatifs sont présents lorsque « les choses ont des rapports ambigus et insaisissables, si des évènements ont lieu mais pas dans le déroulement linéaire du temps, et si des phénomènes partagent un même espace mais ne peuvent pas être analysés en utilisant un seul ensemble d'axes tridimensionnels » (Mol et Law 2002 : 1). Lorsque ces conditions sont satisfaites, le système analysé est vraisemblablement un système complexe ; dès lors, une approche comme l'analyse de réseaux ou la simulation multi-agents peut faciliter son examen.

Les sciences de la complexité nous permettent d'examiner comment les structures d'ordre supérieur (comme les groupes) naissent à partir d'interactions individuelles (les rapports interpersonnels, par exemple). Les sciences de la complexité sont ainsi mieux adaptées pour naviguer dans les eaux troubles de l'archéologie. L'utilité des approches systémiques complexes dans le domaine de l'archéologie a été explorée par R. A. Bentley et H. Maschner (2008), T. Kohler (2012), J. McGlade (1995), J. McGlade et S. Van der Leeuw (1997), T. Kohler et G. Gumerman (2000), et K. Bocinsky (2014). Nous nous inspirons ici de ces ouvrages fondamentaux.

Les assises théoriques des sciences de la complexité par rapport à leur application à l'archéologie peuvent se résumer ainsi :

1. Les individus sont fondamentaux, donc nous devons étudier les actions et les interactions des individus.
2. Les comportements au niveau systémique ne peuvent pas s'expliquer par la somme des parties individuelles. Lorsque les individus interagissent, ils créent des systèmes qui dépassent l'échelle individuelle et qui ne sauraient s'expliquer uniquement par la totalité des stratégies individuelles.
3. Les comportements systémiques comprennent généralement des processus non-linéaires.
4. Le changement et l'adaptation sont caractéristiques des systèmes complexes, mais certains comportements non-adaptatifs peuvent durer et même se développer sous certaines conditions.

Dans un exemple classique du fonctionnement des systèmes complexes, C. W. Reynolds (1987) démontra que les oiseaux de façon individuelle suivent trois règles simples afin de former des nuées complexes : 1. ils maintiennent leur alignement sur le groupe ; 2. ils calculent leur cap à partir du cap moyen pris par leurs voisins ; et 3. ils laissent suffisamment d'espace entre eux et leurs voisins. Quand les oiseaux individuels suivent ces règles, le vol de l'ensemble devient un système complexe et mouvant, capable de répondre aux chocs exogènes (la présence d'obstacle, l'attaque d'un prédateur) d'une manière qui ne saurait être prédite uniquement en considérant les stratégies individuelles. Les sciences de la complexité peuvent ainsi permettre aux chercheurs de saisir des nuances qui seraient autrement masquées par les dynamiques de groupe ; elles peuvent également mettre en exergue des mécanismes qui sont potentiellement responsables de l'émergence de structures de groupe à de plus grandes échelles.

La théorie de la complexité nous fournit ainsi non seulement une nouvelle perspective sur les comportements individuels (les choix de chaque oiseau) ou sur les comportements systémiques (les mouvements du vol), mais aussi sur l'influence que les individus ont les uns sur les autres, et la façon dont les comportements individuels contribuent aux comportement systémiques. Selon la théorie de la complexité, nous devons prêter attention à la façon dont les individus établissent des liens entre eux par le biais de réseaux. Afin de comprendre les caractéristiques des réseaux, nous devons examiner comment l'information et les biens circulent entre les individus. Des changements mineurs dans l'interaction des individus peuvent avoir des conséquences dramatiques et systémiques, mais nous ne pouvons pas comprendre un système en regardant seulement la somme de ses parties.

Cependant, il est évident que les êtres humains sont infiniment plus complexes que les oiseaux. Si nous prenons l'exemple d'un céramique qui voyagea sur 200 kilomètres, il est vraisemblable qu'une ou plusieurs personnes ont pu la faire circuler : nous pouvons éventuellement y voir l'interaction d'une ou de plusieurs personnes liées entre elles par le déplacement de la céramique en question. En outre, il sera ainsi possible de comprendre cette transaction par le biais d'une approche systémique complexe, puisque, selon toute probabilité, les échanges n'étaient pas limités à un seul pot en céramique. En regardant la circulation de plusieurs pots, nous pouvons établir des liens par le biais d'un réseau social, suggérant que des personnes disposant des matières premières échangeaient avec des personnes qui profitaient du produit fini, et qu'un lien était ainsi établi entre deux communautés différentes. Les sciences de la complexité et la théorie des réseaux tout particulièrement nous permettent de "percevoir" les gens qui crées les céramiques mais aussi le réseau commercial (les acheteurs des céramiques) reliant de nombreux acteurs dans un domaine complexe et interconnecté.

Selon la théorie de la complexité, les décisions individuelles sont importantes, car elles ont des effets en cascade sur le système forçant les individus et les groupes à s'adapter. Cette théorie offre donc une nouvelle perspective par rapport aux données archéologiques, servant de pont entre l'archéologie processuelle, pour laquelle les structures et les variables sont fondamentales, et l'archéologie post-processuelle, pour laquelle l'autonomie des individues est primordiale. Nous pouvons de cette façon analyser comment les individus font leurs choix, quel impact ces choix ont sur d'autres individus, et comment l'interaction de tous les individus dans un groupe peut donner naissance à une société. En appliquant un ensemble de règles simples, nous pouvons ainsi espérer analyser à la fois l'individu, la famille, le groupe et la structure globale de la société.

Avant de montrer comment les systèmes complexes adaptatifs peuvent nous aider à comprendre l'émergence de structures hiérarchiques pendant l'époque préhistorique, nous allons brièvement évoquer l'histoire de la théorie archéologique afin de situer les présentes études de cas.

Une approche systémique complexe à la préhistoire : l'exemple de la hiérarchie

À cent ans d'écart, deux philosophes sont intervenus sur la question de la nature innée de l'homme et sa prédisposition pour l'individualisme ou le collectivisme. Th. Hobbes (1651) affirma que les êtres humains sont compétitifs par nature. Exactement cent ans plus tard, J.-J. Rousseau (1751) prit une perspective plus optimiste par rapport à la nature humaine, suggérant que les individus ont tendance à former des collectivités coopératives pour leur bénéfice mutuel.

Néanmoins, nul besoin, alors de choisir entre Th. Hobbes et J.-J. Rousseau afin de comprendre comment les hommes coopèrent et rivalisent entre eux. C'est la voie proposée par le concept de sélection à niveau multiple qui fut développée par D. S. et E. O. Wilson (2008) comme un processus de sélection emboîtée (comme un ensemble de poupées russes). Selon leur théorie, la sélection naturelle de base agit sur l'individu (la plus petite poupée, dans leur analogie), mais d'autres mesures de sélection opposées peuvent également agir sur le groupe (ou des groupes de groupes, les poupées de plus en plus larges), créant ainsi un processus de sélection « emboîtée ». La sélection à niveaux multiples est un moyen d'analyser les processus de niveau inférieur et supérieur (Richerson et Boyd 2005 ; Turchin 2003 ; Turchin et Gavrilets 2009 ; Wilson 2002). La sélection à niveaux multiples nous offre un autre moyen de comprendre comment des processus contradictoires comme l'altruisme et la compétition qui peuvent simultanément jouer des rôles essentiels dans une société donnée.

C'est aussi possible de comprendre l'interaction de la coopération et la compétition avec le concept de hiérarchie. La coopération et la compétition ne s'excluent pas mutuellement. Il existe des niveaux d'interaction différents, auxquels la compétition ou la coopération peuvent servir l'intérêt de l'individu et/ou du groupe (Carballo *et al.* 2014). Les analyses classiques de la hiérarchie se concentrent soit sur une démarche par le haut, descendante (*sensu* Brumfield et Earle 1987 ; Earle 1997 ; Serbvice 1962), soit sur une démarche par le bas, ascendante (*sensu* Fried 1967, présenté dans Pauketat 2007 : 22). Si ces démarches permettent de décrire l'existence de structures hiérarchiques dans un état final, elles ne nous permettent cependant pas de comprendre le développement de ces structures hiérarchiques.

La propagation de l'altruisme à travers un groupe repose sur un équilibre entre les forces de sélection du niveau individuel et des niveaux supérieurs (Turchin et Gavrilets 2009 : 169). « Les groupes humains ont besoin d'être bien intégrés par des mécanismes de coopération à l'intérieur du groupe, afin de pouvoir concurrencer avec d'autres groupes » (Turchin et Gavrilets 2009 : 169). La compétition entre deux ou plusieurs groupes coopératifs en leur sein est une méthode fréquente pour illustrer la sélection à niveaux multiples, démontrant ainsi comment les forces sélectives agissant sur les individus peuvent différer de celles agissant sur les groupes.

Le compromis effectué entre les bénéfices pour l'individu ou pour le groupe est présenté par P. L. Hooper *et al.* (2010). Dans leur modèle mathématique, chaque groupe joue au jeu du bien public suivant un format conçu par McElreath et Boyd (2007). Des individus extraits d'une population nombreuse sont regroupés ensemble de façon aléatoire, et les individus contribuent au bien public. La contribution au bien public coûte quelque chose à chaque individu, mais le bénéfice final est partagé équitablement entre tous les membres du groupe. Comme le bénéfice est distribué à parité indépendamment de la contribution effectuée, et comme les individus exhibant de divers niveaux de coopération, il est tentant pour certains membres de faire défaut. En conséquence, les groupes peuvent choisir soit d'élire un leader pour surveiller la défection qui sera payée par les impôts, ou d'établir des « surveillants réciproques » (*mutual monitors*) non-élus et non-payés pour effectuer la même tâche. Pour les leaders des deux groupes (hiérarchiques et réciproques), la punition coûte aussi à celui qui impose la peine. Les surveillants réciproques réussissent lorsque tout le monde dans le groupe coopère et joue au jeu du bien public, mais à mesure que la taille du groupe augmente, la probabilité de défection et la pression exercée sur les surveillants augmentent en parallèle. En revanche, les groupes hiérarchiques réussissent moins bien lorsque les groupes sont petits, mais à mesure qu'ils croissent, il devient bénéfique de payer un individu pour consacrer tout son temps à surveiller les membres du groupe pour assurer qu'aucune défection n'ait lieu. Il existe des dynamiques de stabilisation pour le nombre de coopérateurs par rapport au nombre de transfuges, ainsi que pour le choix de surveillants réciproques ou de leaders rémunérés. Dans ce modèle, plus la taille du groupe augmente, plus les groupes hiérarchiques reproduisent et réussissent, grâce au fait que le leader élu peut consacrer tout son temps à punir les transfuges. Cet article examine ainsi pourquoi les individus choisissent explicitement des structures hiérarchiques, afin de freiner la défection et accroître la coopération au sein du groupe — une question importante mais que de nombreuses études ont souvent négligée.

T. Kohler *et al.* (2012) ont instancié une version plus nuancée du modèle de P. L. Hooper *et al.* dans le contexte de leur simulation multi-agents semi-réaliste, le modèle « Village » (Kohler et Varien 2012). Dans ce modèle, les groupes hiérarchiques et non-hiérarchiques jouent chacun au jeu du bien public au sein de leur groupe. Dans cette instanciation les groupes étant non-territoriaux, en sens que personne ne possédait aucun territoire, et les agents entremêlés avec les autres. Dans ce modèle, le jeu du bien public se joue avec du maïs, mais comme le modèle correspond à la région des Pueblos du Sud-Ouest des États-Unis, ceci est censé représenter un bien public réel (un mur ou un réservoir, par exemple). Les individus participant aux groupes hiérarchiques enregistrent de meilleurs résultats au fur et à mesure que la taille du groupe augmente, et leurs groupes se multiplient. La capacité des groupes hiérarchiques à effectivement surveiller et prévenir la défection démontre ainsi l'avantage des structures hiérarchiques et comment celles-ci auraient pu se développer au cours de projets liés au bien public.

P. L. Hooper *et al.* et T. Kohler *et al.* ont ainsi utilisé de multiples perspectives afin d'étudier comment les individus (de leur plein gré, selon l'école post-processualiste) abandonnent une certaine partie de leur autonomie pour rejoindre un groupe (pour créer des structures, selon l'école processualiste), afin d'éventuellement augmenter le retour sur le bien public. Leurs travaux nous aident à comprendre pourquoi les individus adhérent à des groupes, clarifiant notre compréhension du développement de structures hiérarchiques. Cependant, dans le modèle de T. Kohler *et al.,* la hiérarchie n'existe qu'au sein du groupe (entre les citoyens ordinaires, et les leaders qui sont responsables pour punir les transfuges et percevoir les impôts). Afin de comprendre les structures hiérarchiques entre les groupes, d'autres méthodes sont nécessaires. À cet égard, les études menées pour définir les caractéristiques organisationnelles des villes nous seront utiles.

D. Pumain (2006 : 179) suggère que nous ne saurions déduire l'importance d'une ville simplement en connaissant sa taille. Il est vrai qu'il est particulière difficile de calculer la taille d'une ville : doit-on la calculer à partir de sa superficie ou de sa population ? En revanche, nous devons saisir l'importance d'une ville par le biais de son rapport avec d'autres communautés. Malheureusement, dans le monde de l'archéologie, il nous reste le plus souvent que l'architecture pour effectuer nos calculs. Au chapitre 4, nous utilisons la taille des sites pour supposer des structures hiérarchiques, mais nous complétons cela avec des données sur la taille des espaces rituels (les kivas), en plus d'une simulation qui développe la hiérarchie. De cette façon, nous ciblons des préoccupations possibles en examinant la hiérarchie non seulement par le biais de la population, mais aussi la taille des espaces rituels et des régimes politiques à travers le temps.

Dans un travail récent, L. M. A. Bettencourt (2013) a démontré que l'infrastructure urbaine illustre une économie d'échelle croissante. La quantité d'infrastructure dont une ville a besoin n'augmente pas de façon linéaire avec sa taille croissante ; en fait, ce besoin est sous-linéaire, tandis que les avantages sociaux conférés par la vie dans une ville croissent plus rapidement que la taille de la ville (en comparant des villes de tailles différentes). Poursuivant ce travail, S. G. Ortman *et al.* (2014 : 2) a postulé que « cette accumulation de fonctions avec la taille de la population fournit également un mécanisme pour la naissance de structures hiérarchiques à l'échelle des habitations qui caractérisent les sociétés à la fois modernes et anciennes. »

D. Pumain observe que (2006 : 174) « Contrairement aux villages (ou aux collectivités minières) qui exploitent les ressources sur leur site même, ou dans les communautés avoisinantes, les villes gagnent leur vie en extrayant les richesses créées par leur *situation* ». Cette situation peut être vu comme d'être pôle important des interactions des citoyens du paysage.

S. G. Ortman *et al.* (2014) démontrent que les sites archéologiques dans le bassin du Mexique révèlent des propriétés d'échelle urbaine semblables à celles identifiées dans nos villes modernes. Les caractéristiques organisationnelles des villes préhistoriques présentent des économies d'échelles similairement croissantes ; elles reflètent vraisemblablement une hiérarchie politique développée afin d'organiser efficacement un peuple nombreux (cependant, voir Froese *et al.* [2014] pour la présentation de la cité aztèque de Tenochtitlan comme une communauté auto-organisée). Les oppida étaient organisée de la même façon ; l'agrégation en oppida progressivement plus larges servait à renforcer toute hiérarchie déjà en place avant l'urbanisation, avec le degré de hiérarchie augmentant selon un gradient allant de la côte jusqu'à l'intérieure (Favory *et al.* 1998 ; Favory *et al.* 1999: 15 ; Garcia 2014 ; Nuninger *et al.* In press). Garcia (2005 : 172) remarque que les premières manifestations de l'urbanisation — c'est-à-dire, l'agrégation en oppida — avaient tendance à se concentrer au sommet de collines ou dans de basses vallées (Garcia 2005 : 173). Les caractéristiques naturelles environnantes ont probablement permis la lente transition vers l'agro-pastoralisme (l'environnement était si généreux pour permis la chasse et la cueillette), les habitants complétant leur mode de vie par des activités locales de pêche et de cueillette. En outre, la fréquence accrue de lieux de stockage, vraisemblablement utilisés pour les surplus agricoles, appuie le développement de grandes économies de commerce, ainsi que le développement de hiérarchies (Nuninger *et al.* In press).

Les travaux de Nuninger (p. ex., 2002 : 89) examinent non seulement l'organisation spatiale des sites, mais également leur organisation hiérarchique. Nuninger identifie quels sites étaient probablement des centres de gravité pour l'habitation dans la région, des sites qui seraient naturellement devenus des pôles importants dans les réseaux locaux. Dans une autre étude des sites du sud de la France, Fovet (2005) a analysé une région de 65 km^2 près de Nîmes pour décrire l'impact d'une installation permanente sur le mode de vie agro-pastoral, allant de l'âge du bronze

(8e siècle avant J.-C.) jusqu'à la fin du Moyen-Âge (15e siècle après J.-C.). Son travail présente non seulement les détails topographiques de la région, mais également sa productivité agro-pastorale potentielle, se basant sur des études recueillies par le projet Archaeomedes (Van der Leeuw *et al.* 2003).

Le travail présenté dans cette thèse n'aborde pas la spatialité de la même façon que Nuninger, Fovet et d'autres. Selon la simulation multi-agents présenté dans le chapitre 3, la spatialité est utilisée pour calculer les coûts d'échange ; le paysage est cependant très simplifié dans ce modèle. Des itérations futures de cette simulation multi-agents pourraient intégrer les données de Nuninger (2002) pour vérifier si les résultats du modèle sont encore valables avec l'incorporation de sites archéologiques réels et de leur densité de population potentielle, ou si les schémas exprimés au chapitre 3 sont en partie lié à un effet du code. Tout particulièrement, les estimations de la densité dans certains villages (entre 250 et 500 habitants sur 1 ou 2 hectares) calculées par Py (1990 : 70) sont beaucoup plus élevées que la densité permise par la simulation, ainsi le fait d'utiliser des données archéologiques plus précises modifierait probablement les résultats.

Raynaud (2000) a remarqué que ces grands établissements solidement fortifiés avaient des aires d'influence qui rayonnaient sur la campagne environnante. Cette influence avait vraisemblablement un effet de stabilisation sur le système de peuplement et les populations des oppida et des fermes situées en périphérie. Les grands centres agrégés, oppida, qui sont apparus aux cours de l'Âge du Fer en France méridionale étaient probablement des bassins d'attraction pour les commerçants méditerranéens arrivent dans la region. Néanmoins, si la stabilité de ces centres avait été perturbée, des migrations massives auraient été probables (Raynaud 2000). L'on peut comparer l'influence exercée par les oppida sur les citoyens des environs avec l'influence de Chaco Canyon pour les Pueblos ; suite à la désintégration de Chaco, le reste du monde pueblo fut bouleversé (Vivian 1996 ; Crown 1994).

Mais comment passer des individus, réunis en groupe pour jouer au jeu du bien public dans les modèles de P. L. Hooper *et al.* et de T. Kohler *et al.*, à la croissance des sites et des villes examinés par L. M. A. Bettencourt et S. G. Ortman *et al.* ? Ici, certains travaux sur le conflit, en particulier le conflit *entre* les groupes, peuvent nous aider à saisir le développement des sociétés hiérarchiques.

Le conflit, et même la menace de conflit, sont une force motrice pour le développement sociétal (Turchin et Gavrilets 2009). P. Turchin et S. Gavrilets (2009 : 170) observent que la guerre force les groupes à augmenter leur cohésion interne, crée des progrès technologiques et peut accroître la taille du groupe. Selon eux, le développement de la hiérarchie est fondé sur le désir d'éviter le conflit (ou au moins d'en sortir vainqueur).

> La croissance de sociétés organisées de manière hiérarchique a lieu principalement lorsque les chefs de villages annexent des villages subordonnés et rajoutent de nouvelles couches hiérarchiques aux couches préexistantes. Par conséquent, les sociétés hiérarchiques ne sont pas limitées par la capacité du canal social, et n'ont théoriquement pas de taille limite (Turchin et Gavrilets 2007 : 171).

P. Turchin et S. Gavrilets (2009 : 172) suggèrent aussi que si le développement de structures hiérarchiques est un processus naturel, les hiérarchies présentes « devraient refléter cette histoire évolutionnaire, tout comme les organismes biologiques conservent de nombreuses traces de leur histoire évolutionnaire ». Ils poursuivent : « toutes les sociétés humaines, même les plus simples (contrastant avec les sociétés d'envergure des insectes sociaux), sont organisées de manière hiérarchique » (Turchin et Gavrilets 2009 : 172). Ceci est vrai même au sein de groupes qui s'auto-organisent : les individus forment des familles, et les familles forment des lignées ou des villages. Ces structures emboîtées peuvent être considérées comme inhérentes aux hiérarchies ; nous pouvons ainsi nous en servir pour comprendre les sociétés du passé.

Comme en témoignent les travaux de S. G. Ortman *et al.* (2014), les sciences de la complexité s'associent parfaitement avec les riches jeux de données fournis par de nombreux projets archéologiques. Des efforts ont récemment été consentis pour synthétiser les données sur de larges régions avec des bases de données détaillées en utilisant les résultats des travaux historiques et archéologiques ainsi que les nombreuses données fournies par des projets d'envergure (Bettencourt 2013 ; Kohler et Reese 2014 ; Klingenstein *et al.* 2014 ; Mills *et al.* 2013 ; Ortman *et al*. 2014 ; Schwindt *et al*. 2015).

Alors que les sciences de la complexité peuvent poser des questions différentes de celles posées par l'archéologie classique, ces études reposent néanmoins sur plus d'un siècle de recherche classique en archéologie. Par exemple, les travaux d'Alfred V. Kidder (1924) ont joué un rôle clé dans l'avancement de la recherche archéologique dans le Sud-Ouest des États-Unis, en particulier en contribuant à sa cohérence chronologique ; sa chronologie s'utilise encore de nos jours pour évoquer l'archéologie des Pueblos. Plus d'un demi-siècle plus tard, le travail entrepris par le Dolores Archaeological Project (Breternitz *et al.* 1986) aida à compléter la recherche sur les établissements Pueblos, en particulier pendant les époques Basketmaker (les vanniers) et Pueblo I. Des études récentes ont poursuivi cette recherche, essayant de saisir les processus de hiérarchisation du passé et de comprendre comment les structures d'une société peuvent être identifiées par la taille et l'emplacement de structures matérielles (Kohler et Higgins *à paraître* ; Schachner 2001, 2010 ; Ware 2014). En France méridionale, les études archéologiques des sociétés de l'âge du bronze et de l'âge du fer reposent principalement sur le travail fondamental de Michel Py (1990, 2012) et Dominique Garcia (2005, 2014) dont la capacité pour comprendre, repérer et synthétiser la protohistoire de la région rappelle le génie de V. Gordon Childe (1936). S'inspirant du travail de M. Py, M. Dietler (par ex., 1990 ; 2010) inscrit la Gaule méridionale dans un vaste réseau d'interactions avec le reste du monde antique.

Ce qui ressort clairement de toute cette discussion est que les approches systémiques complexes s'articulent bien avec nos tentatives pour comprendre le développement de structures hiérarchiques, étant donné le rôle clé de l'émergence dans les deux cas. Or l'étude du développement de la hiérarchie serait impossible sans pouvoir interroger les actions — et interactions — des individus. Les individus interagissent ensemble, et ils peuvent choisir un leader pour gérer le bien public et prévenir la défection de membres du groupes, entraînant ainsi une croissance hiérarchique. Il est donc possible d'examiner l'individu et son autonomie, ou le groupe et sa structure, au sein de la même étude.

La hiérarchie est aussi évidente en Gaule méridionale ; l'époque qui est étudiée dans cette thèse est marquée par une hiérarchie sociale déjà établie depuis plusieurs générations. Quand j'analyse l'échange de céréales pour le vin, j'examine implicitement comment un bien de luxe (le vin) influe sur la production des aliments de base (les céréales) dont le surplus est au bénéfice des aristocrates gaulois, creusant ainsi la différenciation sociale. Le vin n'était semble-t-il pas une denrée accessible au peuple, excepté peut-être lors de fêtes cultuelles, car il a été retrouvé exclusivement dans les maisons et les sépultures des élites. C'est un bien qui bénéficie d'une valeur symbolique qui a renforcé la hiérarchie sociale, donc quand j'analyse le remplacement d'un bien de luxe (les amphores étrusques) par un autre (les amphores grecques), ce qui permet de contribuer aux études sur le processus de hiérarchisation. Ainsi, en construisant des modèles nous pouvons examiner comment l'échange des biens de luxe a influencé le développement et le maintien du système hiérarchique social des Gaulois dans le contexte colonial associé au développement des marchés méditerranéens.

Bien que des décennies de recherches se soient concentrées sur l'étude interculturelle des systèmes humains, la construction de modèles (SMA ou autrement) et leur épreuve théorique offrent une nouvelle façon d'appréhender le monde, répondant ainsi à des questions qui seraient inabordables d'un point de vue traditionnel (Lake 2014). Au lieu d'observer la panoplie de la culture humaine pour en dégager des motifs, nous pouvons élaborer des théories, construire des modèles sur la base de ces théories, et enfin en comparer les résultats avec les données.

La construction de modèles

Un modèle est un microcosme idéalisé d'un système réel élaboré à partir d'une théorie ; ou, comme D. Clarke (1972 : 2) l'explique, « les modèles sont les pièces de machinerie qui articulent les observations avec les idées théoriques ». Même les modèles élaborés à partir de règles très simples peuvent aider à éliminer de mauvaises hypothèses et à élucider le fonctionnement d'un système. En outre, même lorsqu'un modèle est faux (« tous les modèles sont faux, mais certains sont utiles » [Box et Draper 1983 : 424]), nous pouvons néanmoins collecter des informations par rapport au système qu'il représente en développant progressivement le modèle et en étudiant les processus simplifiés de systèmes complexes. De ce point de vue, le modèle à une valeur heuristique interessante dans un domaine où les processus ne sont pas directement renseignés par les données accessibles. Pour l'étude des processus, l'une des formes de modélisation les plus efficaces est la simulation multi-agents.

Qu'est-ce que la simulation multi-agents ? La simulation multi-agents est un puissant outil de simulation informatique, mais c'est tout d'abord un instrument qui permet de comprendre des comportements qui demeureraient autrement insaisissables. La simulation multi-agents est utile pour identifier comment les comportements globaux émergent de décisions individuelles, lorsque ces comportements sont trop compliqués pour être représentés par une série d'équations différentielles. Dans une simulation multi-agents, les agents sont les unités que nous souhaitons étudier : des cellules, des personnes, des familles, même des villes. Ensuite des règles de comportement dans diverses situations sont imposées, et les agents agissent par rapport à ces règles dans un environnement virtuel suivant une chronologie simulée. Les interactions en sont le résultat ; lorsque c'est possible, les motifs créés par les agents sont comparés avec ceux identifiés dans les données archéologiques.

A. Costopoulos, M. Lake et N. Gupta expliquent que :

> Les simulations peuvent nous surprendre. Que la surprise soit due à notre mauvaise compréhension de la réalité modélisée, ou de la réalité que nous souhaitons appréhender, les simulations peuvent nous obliger à revoir nos hypothèses et aller au-delà des modèles intuitifs du passé qui nous séduisent trop souvent (Costopoulos *et al.* 2010 : 2).

Les simulations nous aident ainsi à examiner les théories que nous avons élaborées à propos du monde et, en conséquence, à développer de nouveaux modèles plus performants pour décrire ce monde. Il existe alors une boucle de rétroaction entre les outils des sciences de la complexité (les simulations) et les théories elles-mêmes. Les simulations et les sciences de la complexité nous obligent à revoir la façon dont on voit le monde. Les simulations nous permettent de mettre à l'épreuve des théories développées par des anthropologues et des historiens sur la base d'années de recherche interculturelle (Lake 2014 : 699). Les simulations peuvent aussi cibler des questions différentes par rapport à la recherche interculturelle, en nous aidant à revoir les hypothèses archéologiques existantes.

Les simulations multi-agents élaborées conjointement avec la recherche en matière de systèmes complexes adaptatifs permettent l'analyse directe d'individus et de structures globales. La plateforme « Swarm » fut une des premières simulations multi-agents développées par le Santa Fe Institute, lui-même une des premières institutions à étudier les systèmes complexes adaptatifs (Kohler et Gumerman 2000). Dans cette thèse, les outils fournis par les systèmes complexes adaptatifs — la simulation multi-agents et l'analyse de réseaux — sont utilisés afin de comprendre la préhistoire du Sud-Ouest des États-Unis et la protohistoire de la France méridionale. Employés de manière conjointe, ces outils nous permettent d'apprécier les rapports entre les décisions et les comportements individuels et les structures au niveau du groupe.

Les réseaux

Mais pourquoi évoquer les réseaux ? Comme le suggère Carl Knappett (2011 : 10), et T. Brughmans (2012 : 3), parce que :

> 1. [Les réseaux] nous obligent à considérer les relations entre les entités ; 2. Ils sont intrinsèquement spatiaux, avec la flexibilité d'être à la fois sociaux et physiques ; 3. Les réseaux sont une bonne méthode pour articuler les échelles ; 4. Les réseaux peuvent intégrer à la fois des personnes et des objets ; 5. Des travaux récents sur l'analyse des réseaux intègrent une dimension temporelle (Knappett 2011 : 10).

Selon C. Knappett (2011), les réseaux offrent une manière de conceptualiser les entités dans l'espace et à travers le temps, ce qui présente des avantages méthodologiques à cause de la structure complexe des réseaux. Les études de réseaux varient considérablement par rapport à leurs systèmes de référence, allant de l'analyse des interactions sociales à l'examen de la manière dont les espèces interagissent au sein d'un réseau trophique, et bien au-delà (Evans et Felder 2014). Cependant, le trait partagé par toutes les études de réseaux demeure l'idée que les rapports entre les entités importent autant que les entités elles-mêmes (Brughmans 2012).

L'analyse de réseaux subit actuellement une période d'intensification dans les sciences sociales. Nous connaissons déjà l'analyse des réseaux sociaux, par exemple des interactions sur Facebook, comme celles présentées par les médias (Backstrom et Kleinberg 2013). Mais dans le domaine de l'anthropologie aussi, les études de réseaux ne cessent de se multiplier (voir, par exemple, Evans et Felder 2014). Quoique des approches de réseau aient été utilisées depuis les années 1950 et 1960 (Epstein 1969 ; Erdős et Renyi 1959 ; Erdős et Renyi 1960 ; Erdős and Renyi 1961), grâce à nos approches modernes, nous pouvons maintenant manipuler de larges jeux de données afin de comprendre non seulement comment les individus interagissent, mais aussi comment les systèmes changent en fonction de ces interactions interpersonnelles.

Nous utilisons ici le terme « réseau » pour signifier un graphique avec des nœuds et des liens (Brughmans 2012). Les nœuds sont les acteurs du réseau, qu'ils soient des personnes, des groupes, ou même des espèces. Les liens précisent quels nœuds interagissent et comment ; les « bords » font généralement référence aux liens non-orientés, tandis que les « arcs » font généralement référence aux liens orientés (Hanneman et Riddle 2005 ; Wasserman et Faust 1994). L'identification des différences entre les deux grandes approches de l'analyse de réseaux – l'analyse des réseaux sociaux et l'analyse des réseaux trophiques –, sera d'une importance capitale dans cette thèse.

L'analyse des réseaux sociaux concerne la façon dont les personnes sont connectées entre elles (voir ci-dessous), tandis que l'analyse des réseaux trophiques concerne la façon dont les producteurs et les consommateurs sont connectés au sein d'un écosystème par le biais des modèles de consommation. T. Brughmans (2012 :10) remarque qu'à ses débuts, l'analyse des réseaux sociaux est issue de la sociométrie, une science développée pendant les années 1930 par des chercheurs à Harvard (Moreno 1934, 1946, 1960 ; Moreno et Jennings 1938). La sociométrie voulait représenter les rapports interpersonnels dans un espace bidimensionnel (un graphique). L. C. Freeman (2004 : 30) soutient que la sociométrie « était la première science à réunir tous les éléments caractéristiques de l'analyse des réseaux sociaux ».

L'étude des réseaux trophiques a également de profondes racines théoriques. Le plus ancien graphique d'un réseau trophique est attribué à Lorenzo Camareno (1880), avec des travaux identiques effectués par V. Shelford (1913) et V. S. Summerhayes et C. S. Elton (1923 ; il est présenté dans Egerton 2007). Des décennies plus tard, P. Yodzis et S. Inness (1992) ont structuré la façon dont les producteurs et les consommateurs sont reliés par des réseaux trophiques crées par les rapports entre la création de biomasse et la prédation. En 1998, J. A. Estes *et al.* ont créé le premier modèle de réseau trophique d'un système littoral océanique, en analysant la réponse fonctionnelle de la prédation des loutres de mer par les orques. Cette étude est considérée comme une des études marquantes pour l'analyse moderne des réseaux trophiques.

De récentes applications de l'analyse trophique ont incorporé les êtres humains dans les réseaux trophiques, illustrant que ceux-ci font partie des écosystèmes et ne sont pas des éléments à part. Par exemple, Maschner *et al.* (2009) ont démontré que l'abattage de lions de mer pour leur peau dans la fabrication de kayaks a vraisemblablement maintenu la population des lions de mer suffisamment basse pour diminuer la pression sur la pêche en Alaska, tandis que Coll *et al.* (2011) ont examiné l'incidence des humains sur la population des zostères maritimes et la diversité dans de multiples communautés. Contrant H. Maschner *et al.,* G. Murphy et T. N. Romanuk (2014) ont analysé comment les perturbations humaines nuisent à la diversité des espèces. Ces deux études démontrent comment les humains peuvent devenir des cultivateurs de la richesse des espèces (Maschner *et al.* 2009), ou des destructeurs de la biodiversité (Murphy et Romanuk 2014).

Les liens sont toujours orientés dans l'analyse des réseaux trophiques, avec une espèce consommant une autre. Il y a des cas réciproques, où une espèce consommera et sera consommée comme proie par une autre espèce (les loups et les couguars, par exemple, peuvent s'entremanger dans certains cas), mais la caractéristique essentielle des réseaux trophiques demeure la directionalité des liens alimentaires. Une analyse typique d'un réseau trophique comprend souvent l'épreuve de la résilience du réseau à l'extinction par l'élimination d'une ou de plusieurs espèces (par ex., Binzer *et al*. 2011 ; Brose 2011) ; l'examen des effets de changements dans l'alimentation des espèces clés (par ex., Ramos-Jilberto *et al.* 2011) ; l'examen de la baisse (ou de l'augmentation) de la diversité des espèces (par ex., Murphy et Romanuk 2014 ; Romanuk *et al*. 2009) ; ou l'examen de l'impact de divers types fonctionnels d'espèces, tels les parasites, sur le réseau (Dunne *et al*. 2013).

Contrairement aux réseaux trophiques, les réseaux sociaux peuvent avoir des liens orientés (des amitiés unilatérales, des dons) et des liens non-orientés (des amitiés réciproques, des cadeaux réciproques). Certaines des mesures communes aux analyses des réseaux sociaux des données archéologiques sont des indices de centralité : la centralité de degré, la centralité d'intermédiarité, et la centralité de vecteur propre (Brughmans 2012 : 14). De tels indices ont été employés afin de souligner l'importance de sites particuliers dans le contexte d'évènements migratoires (Mills *et al.* 2013), du développement de Cahokia en tant que centre politique majeur (Peregrine 1991 : 68), et de la diffusion de la poterie à travers le monde romain (Brughmans 2010). Les indices de centralité sont utiles pour l'archéologie car ils révèlent quels nœuds sont les plus importants pour le fonctionnement du réseau, avec des implications conséquentes pour la taille et l'emplacement d'un site. En inversant cette logique, de tels indices pourraient peut-être expliquer comment ou pourquoi certains sites devinrent importants.

La science des réseaux sert ainsi de pont entre les détails locaux des nœuds et la structure globale d'un système (comme la simulation multi-agents, qui représente et l'autonomie des acteurs individuels et la structure du système). T. Brughmans maintient que « la combinaison d'analyses des réseaux sociaux et de techniques de simulation de réseaux complexes semble détenir un véritable potentiel pour l'étude des réseaux en archéologie » (Brughmans 2012 : 19).

Dans une étude récente qui illustre l'utilisation des réseaux sociaux en archéologie, A. C. F. Collar (2007) explore l'innovation religieuse sous l'angle de l'invention du monothéisme pendant l'Empire romain. Elle examine la façon dont les idées religieuses circulaient dans le réseau religieux du culte des Hypsistariens, et comment l'orthodoxie chrétienne acquit une position dominante. Elle suggère que la théorie du « phénomène du petit monde », ou celle de la « cascade d'innovations » (Collar 2007 : 150), peuvent expliquer comment le monothéisme se diffusa avec un tel succès pendant le déclin de l'Empire romain. Les travaux de A. C. F. Collar démontrent comment analyser les données archéologiques à travers l'optique de la science des réseaux, utilisant la théorie de la complexité pour comprendre comment un phénomène complexe observé (la dominance de religion chrétienne) peut être le résultat des actions simples de personnes clés (des nœuds importants qui influencent tout le système).

Dans une autre étude marquante, B. J. Mills *et al.* (2013) ont utilisé les réseaux afin d'analyser la similarité des arts céramiques à travers le Sud-Ouest des États-Unis, suggérant que de tels réseaux permettent l'émergence de distinctions de valeur archéologique (par exemple, des frontières ethniques à superposer sur des sites et des régions). Les points forts de cette étude sont tout d'abord son énorme fichier de données, et en second lieu, sa représentation graphique de la connectivité dans le Sud-Ouest — une représentation difficile à obtenir avec un modèle verbal.

Les réseaux de communication sont aussi importants pour comprendre la préhistoire. Garcia (2005 : 174) observe que les réseaux de communication et de commerce étaient décisifs par rapport aux choix que les peuples de l'âge du fer effectuèrent quant à l'emplacement de leurs villages. Il identifie quatre caractéristiques nécessaires pour le développement de l'urbanisation :

1. un surplus agricole ;
2. l'établissement du commerce ;
3. la cohésion du groupe ; et
4. l'émergence d'un pouvoir politique.

Les deux premières caractéristiques sont explicitement modélisées dans l'article présenté au chapitre 3. Quoique la troisième caractéristique soit supposée par le modèle, agents impliqués dans un rapport commercial ayant plus de chance d'habiter plus près l'un de l'autre, la cohésion du groupe ne se solidifie jamais explicitement. En outre, le modèle présenté au chapitre 3 ne démontre pas l'émergence d'un pouvoir politique ; il traite plutôt tous les agents comme des acteurs autonomes sans égard à une structure hiérarchique quelconque. Le modèle présenté au chapitre

4, par contre, décrit explicitement l'émergence d'un pouvoir politique, tout en restant basé sur les quatre caractéristiques définies par Garcia (2005). L'on peut suggérer que lorsque les processus modélisés au chapitre 3 seront développés davantage, ils pourront aboutir aux régimes politiques complexes qui sont présentés au chapitre 4.

Deux des avantages de la science des réseaux pour l'archéologie sont les suivants :

• Elle permet l'analyse et la représentation de la connectivité entre les nœuds d'une façon qui se prête à la comparaison entre des réseaux différents, et fournit des interprétations intuitives et analytiques de concepts abstraits telle que la centralité ;

• Elle peut souligner la vulnérabilité d'un système : on peut voir exactement comment le réseau répond lorsque des nœuds sont éliminés, et l'on peut ainsi prédire comment le système se reconfigurera à la suite de perturbations externes.

Trouver l'invisible grâce aux approches systémiques complexes

Nous avons commencé ce chapitre en suggérant qu'il est difficile de comprendre les rapports humains préhistorique en se servant des méthodes classiques de la science archéologique. Le fait que les artefacts se conservent, tandis que les rapports disparaissent, se posent comme une problématique importante pour l'étude de l'humanité.

Néanmoins, les systèmes complexes adaptatifs offrent une autre façon d'examiner les rapports entre les individus du passé. En se servant de telles méthodes, nous pouvons directement observer comment les individus prennent des décisions (par le biais de simulations multi-agents) ou se relient à d'autres individus (par le biais d'analyses de réseaux), analysant ensuite les effets de ces actions et interactions sur une structure d'ensemble. Une approche se basant sur les systèmes complexes adaptatifs nous aident ainsi à faire progresser la recherche archéologique afin d'étudier non seulement le tangible (les artefacts), mais aussi l'invisible (les rapports humains).

Une telle approche nous permet d'analyser de multiples échelles d'interaction, dépassant les limites imposées par la recherche classique. Revenant aux positions exprimées par Th. Hobbes et J.-J. Rousseau — l'homme est-il compétitif ou coopératif ? — il nous semble que la « bonne » réponse dépendra vraisemblablement de l'échelle de l'analyse. En nous permettant de relier plusieurs échelles différentes, les systèmes complexes adaptatifs peuvent nous aider à comprendre comment les individus, qui par définition se doivent d'être égocentriques, se regroupent dans des communautés collectives et stables.

La théorie de la complexité permet de déchiffrer les données archéologiques. Nous pouvons observer une volée d'oiseaux et en déduire leurs comportements individuels ; de même, nous pouvons regarder les données archéologiques, qui sont de par leur nature sous forme agrégée, et voir comment elles sont le résultat de choix individuels. Comme M. Dietler (1990 : 381) l'a affirmé à propos de l'âge du bronze et l'âge du fer en France, « les changements culturels sont les conséquences involontaires d'une combinaison de décisions et d'actions effectuées par des individus et des maisonnées expérimentant avec le changement, plutôt que par des cultures ou des sociétés ». Involontairement, M. Dietler évoque une théorie parallèle à celle de la complexité : ce sont les choix des individus qui provoquent les changements sociaux.

Au chapitre suivant, nous interrogeons l'hypothèse de M. Dietler, qui évoquait spécifiquement la France méridionale, en observant comment les choix individuels de gaulois ont pu influencer la culture matérielle du Languedoc-Roussillon. Ce chapitre considèrera donc les réseaux économiques dans une simulation multi-agents et l'analyse de deux échelles différentes : les échanges individuels et régionaux. Cette analyse introduit la théorie de la complexité d'une manière hautement simplifiée et théorique. Cependant, bien que ce modèle soit simple, il nous permet d'avoir accès à des rapports invisibles quoique sous-jacents — dans ce cas particulier, les échanges entre les gaulois et les marchands de passage — afin d'évaluer comment ces rapports ont pu marquer les données archéologiques.

Nous espérons ainsi qu'à travers la recherche présentée, il deviendra possible d'avoir de nouvelles perspectives pour étudier les peuples de la préhistoire, les structures sociales qu'ils créèrent, et les effets de ces structures sur l'environnement dans son ensemble.

CHAPTER 3: A SIMPLE SIMULATION OF SOUTHERN FRANCE

One of the biggest challenges in archaeology is how to examine *things* (e.g., artifacts) to understand *people* and *behaviors*. While the archaeological record is littered with fragments of objects, inferring relationships among people from those objects is inherently difficult. In Southern France this is the case—relationships between native Gauls and visiting Etruscan and Greek merchants must be inferred from the left behind objects, such as discarded amphorae, standing architecture, and/or the physical placement of the highly aggregated towns known as *oppida*.

Nuninger's (2002:89) work is one example of how to examine relationships among villages. She examined not only the spatial organization of sites, but also the hierarchical organization of the sites, determining which sites were likely to be gravitational centers for habitation in the region, which then would naturally become hubs in the local network. Others have suggest (e.g., Favory et al. 1999: 15; Garcia 2014; Nuninger et al. in press) that the process of aggregation into large oppida further intensified any type of hierarchy that may have been in place prior to urbanization with a gradation of intensity from the coast inland. The increasing frequency of storage facilities, which were likely used for agricultural surplus, Nuninger et al. (in press) find supports the development of complex trade economies, as well as the development of hierarchy. Each of these studies demonstrates how a computational modeling approach, in this case a GIS approach, can help to understand relationships among people in prehistory.

In another study using GIS analysis of southern France, Fovet (2005) analyzed a 65 square-kilometer area near Nîmes for the impact that permanent settlement had on an agro-pastoral lifeway for a period of time from the Bronze Age (8^{th} century B.C.) through the Middle Ages (15^{th} century A.D.). Her work demonstrates not only the topographical details of the area, but also the agricultural/pastoral potential productivity of the landscape, built on studies compiled by Archaeomedes (Van der Leeuw et al. 2003).

The agent-based model presented below does not treat spatiality with the same nuance that Nuninger, Fovet, and others have done. Rather, in the model presented below, spatiality is used to determine the costs of trade, but the landscape is highly simplified for this simple model. Future iterations of this model would be wise to use data derived from Nuninger (2002) to test whether or not the results from the model hold true with the placement of real archaeological sites and their density, or if the patterns expressed in the below model are merely artifacts of the code. Specifically, Py's estimates (1990: 70) of density in some settlements—of 250 to 500 inhabitants in 1 to 2 hectares—are remarkably higher than the density allowed in the simulation, so using more precise data derived from the archaeological record would likely influence the results.

The following paper specifically asks the question: what caused the complete switch in wine amphorae from Etruscan to Greek styles in the Languedoc when clearly both Etruscans and Greeks were concomitantly present? A pattern oriented modeling approach (Grimm et al. 2005) was used to examine the overall process of artifact transition and to validate the model with the archaeological record. The findings by French researchers (e.g., Garcia 2014; Nuninger et al. in press; Py 2012) regarding the growth of storage facilities in this region directly influences the assumptions in this model that Gaulish farmers would create grain surplus to use for trade, specifically trading grain for wine. This research is one of the first forays into agent-based modeling of the archaeological record in France, thus it represents both the utility of agent-based modeling for examining the prehistory in France and also acts as a first step for more complex models on French prehistory.

Recently, Nuninger et al. (in press) have thoroughly described this period of immense change in southern France, focusing on the processes that would have led to the growth of large aggregated villages within the region. While the archaeology of the region is well-defined, the modeling approach applied below (and described in Nuninger et al. in press) focuses on the specific effects of the introduction of luxury trade in this region.

It is worth mentioning that not every Gaul would have been drinking wine in prehistory. Indeed, when wine was introduced it was a luxury item, consumed only by those who could afford the luxury. This dynamic is explored in this paper by only allowing those Gauls who accumulate surplus (who are "wealthy") to trade. This research implies that the wealthy Gauls were the drivers of the economy of proto-historic France, and that the trade and consumption of wine was one method to help reinforce the hierarchy that was already present when the merchants arrived. As wealthy families patronized one wine producer over another, this would have created relationships between the consumers and producers, affecting the viability of certain viticultural families over others.

While the consumption of wine reinforced hierarchy for wealthy Gauls, it also would have helped with the survival of Etruscan and Greek merchants. In the following model this is explored through the trade of grain. Merchant-agents can only farm grapes, and thus are dependent on Gauls for their caloric (grain) needs. The establishment of mutual trade relationships thus helps merchants survive, and reinforces the hierarchy for the Gauls.

This model is highly simplified, enabling the examination of a single process: the distribution of wine on the landscape. I do not take into account how trade ventures could lead to aggregation, how different types of technology (e.g. carts and oxen vs. boats) could lead toward decreases in trade costs, and I do not take into account the possibility that individual merchants may have had different strategies for trading their goods. These are fruitful areas for future ventures.

Land **2016**, *4*, 1-x manuscripts; doi:10.3390/land40x000x

OPEN ACCESS

land

ISSN 2073-445X

www.mdpi.com/journal/land/

Article

Simulating Littoral Trade: Modeling the trade of wine in the Bronze to Iron Age transition in Southern France

Stefani Crabtree [1,2,*]

[1] Washington State University, Department of Anthropology, P.O. Box 644910, Pullman WA 91164-4910, U.S.A.; E-Mail: stefani.crabtree@wsu.edu

[2] Université de Franche-Comté, Maison des Sciences de l'Homme et l'Environnement, 32 Rue Megevand, 25030 Besancon Cedex, France +33 3 81 66 51 51

* Author to whom correspondence should be addressed; E-Mail: stefani.crabtree@wsu.edu; Tel.: +1-509-335-3441

Academic Editor:

Published:

Abstract: The Languedoc-Roussillon region of southern France is well known today for producing full-bodied red wines. Yet wine grapes are not native to France. Additionally, wine was not developed indigenously first. In the 7th century B.C. Etruscan merchants bringing wine landed on the shores of the Languedoc and established trade relationships with the native Gauls, later creating local viticulture, and laying the foundation for a strong cultural identity of French wine production and setting in motion a multi-billion dollar industry. This paper examines the first five centuries of wine consumption (from ~600 B.C. to ~ 100 B.C.), analyzing how preference of one type of luxury good over another created distinctive artifact patterns in the archaeological record. I create a simple agent-based model to examine how the trade of comestibles for wine led to a growing economy and a distinctive patterning of artifacts in the archaeological record of southern France. This model helps shed light on the processes that led to centuries of peaceable relationships with colonial merchants, and interacts with scholarly debate on why Etruscan amphorae are replaced by Greek amphorae so swiftly and completely.

Keywords: Languedoc; Gaul; Agent-based model; Trade; Economics; Lattes; Lattara

> Niketas then asked for some wine and poured a cup for Baudolino. 'See if you like this. It's a resinous wine that many Latins find disgusting; they say it tastes of mold.' Assured by Baudolino that this Greek nectar was his favorite drink, Niketas settled down to hear his story. -- Umberto Eco (2000: 27) from Baudolino.

1. Introduction

Understanding the choices that people made in the past is difficult, if not impossible, without written sources directly telling us why people chose specific courses of action. Yet it is these choices that led to the archaeological record; today we can see the aggregate of these decisions. The following model presents a simple case of examining prehistoric economies. Through using an agent-based model on a heterogeneous population it is suggested that the economy of this area was driven by the choices of Gauls as consumers, and not by the availability of goods; this work articulates with longstanding debates in the prehistory of France.

This research specifically asks the question: what caused the complete switch in wine amphorae from Etruscan to Greek styles in the Languedoc when clearly both groups were present on the landscape? This model aims to examine the abrupt transition from Etruscan amphorae to Greek amphorae as discovered by Py (1990) and reported in Figure 3.1 by modeling strictly local processes. A pattern oriented modeling approach (Grimm et al 2005) was used to examine the overall process and validate the model with the archaeological record. Validation in this model is via a complete shift in artifact types from Etruscan to Greek amphorae—output from the simulation is directly compared against output from the archaeological record. This research is one of the first forays into formal modeling of the archaeological record in France, thus this article represents both the utility of agent-based modeling for examining the prehistory in France, and also acts as a first step for more complex models on French prehistory.

The article is organized as follows. First, a brief background situates the research and the research question. Next, methods and then the model is presented; please note that much of the model detail is described in the supplementary ODD protocol to allow for a streamlined description. Results follow, focusing on those outputs that directly facilitate comparison with observed archaeological phenomena. Following the results of the model, a lengthy discussion of the cultural history of southern France is presented, showing exactly how this model articulates with research in this area. Much of the data on this region is published in French; thus this article provides a summary of the culture history in English, advancing understanding for this area for the Anglophone audience. Finally, the archaeological data are discussed in conjunction with the results presented here, and suggestions to future directions are presented.

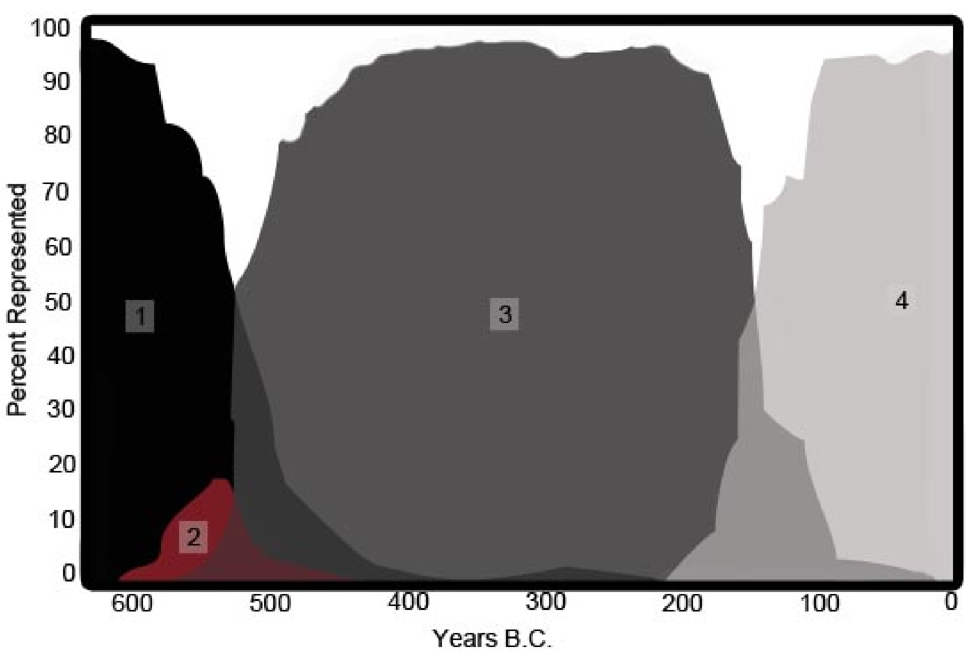


Figure 3.1. Redrawn from Py (1990), curves of artifact percentages through time. (1) represents Etruscan amphorae, which make up almost 100% of the assemblage at that time. (2) represents archaic Greek amphorae, which have a small percentage of the assemblage. (3) represents Greek amphorae. Note that while Greek amphorae are the dominant form of wine vessels after 500 B.C. that amphorae of Etruscan type (1) are still present into the 3rd millennium B.C. (4) represents Roman amphorae, which are not examined in this paper.

1.1 Background

The Languedoc-Roussillon region of southern France (Figure 3.2) is well known today for producing full-bodied red wines. Yet wine grapes were introduced in antiquity. In the 7th century B.C. wine-bearing Etruscan merchants landed on the shores of the Languedoc and established trade relationships with the native Gauls. In fact, most wine consumed in southern France was not even grown by Gauls, instead being imported to Gaulish settlements (Briggs 2003; Dietler 2010). In complement to this, some argue that certain colonial settlements were so large they outstripped their local carrying capacities, and thus had to import grain and other comestibles (Dietler 2010:109). Complex economic partnerships linking Gauls to Etruscan and later to Greek merchants were essential, yet these trade relationships had far-reaching effects for the household economies of both indigenous and colonist populations. "Greek [colonist] towns in general and Greek houses in particular, constitute evidence of a new type of materialism, individualism and consumer display, where patron−client relations were negotiated in semi−public homes, in which creators of wealth were linked to local and international business opportunities" (Bintliff 2014:289). In this paper, I examine how the trade relationships between colonist merchants and indigenous Gauls facilitated the development of complex economies and created distinctive artifact patternings in the archaeological record.

This model examines three processes: 1) the arrival of wine-bearing merchants in Gaul; 2) the establishment of trade relationships between these merchants and native Gauls; and, 3) the replacement of Etruscan wine amphorae by Greek wine amphorae. To understand the establishment of trade between Gauls and colonial merchants we need to understand why Gauls would engage in trading grain for wine. Then, to understand the replacement of one amphora type by another, we need to examine the choices made by Gauls at home. After all, Gauls were the agents of demand in the supply chain. As in the above quote, the preference for one type of wine over another would influence how people would choose to consume wine. Agent-based modeling is a perfect method for examining how local decisions could affect overarching patterns of artifact distributions.

The agent-based model presented here looks at the distribution of artifact types over time across a simplified landscape. By reducing the model to a few key parameters, I am able to directly examine how a preference for one type of wine over the other might affect archaeological assemblages. This model articulates with current debates over the nature of trade within this region. As I discuss below, ethnic identities in the past are difficult to identify, but patterns of artifacts across space and through time can be identified. This simple agent-based model acts as a first step to understanding economies in prehistory and sets up studies that can further examine land use in the past.

Existing models for the interaction between Gaulish inhabitants and colonial traders along the littoral (the region abutting the Mediterranean) of southern France are descriptive. According to Py (2012:135) the paradigms underlying research by proto-historians working in these contexts can be summarized as follows: indigenous Gauls living along the littoral zone were forced to abandon some of their traditional practices, such as semi-nomadic pastoralism, to generate the agricultural surplus required to develop their economies and engage in trade with outsiders (Py 2012). Yet these descriptive models have not been formally tested; thus, the research here formally examines how early colonialism can create distinctive economic partnerships and artifact patterns.

The terms "colonist," "colonizer," and "colonialism" come with academic baggage. To avoid confusion, and differentiate the colonization in southern Gaul from Colonialism in the

1600s-1900s, I will use the term “settled nonlocal merchants,” “settled merchants,” or simply “merchants” henceforth to refer to the Etruscan and Greek merchants. Settled, because in general the colonizers who arrived in southern Gaul settled in colonies, or in already established Gaulish settlements, as is argued for the Etruscans at Lattara (Dietler 2012: 97). Nonlocal, because the first wave of Etruscans and Greeks were born in other areas. (Through time this becomes debatable, as later generations of merchants may have been born in Gaul.) And finally I use the term merchants, because the Etruscans and Greeks who came to southern Gaul are characterized by engaging in trade with the locals.

How the development of agricultural surplus could lead to trade relationships with merchants is directly examined in the model presented here. By creating multiple parameters related to flows of exchange and the ability to extract resources (discussed in more detail below) and sweeping across values for these parameters I can directly examine existing conceptual models for southern Gaul. To state it simply, this model directly examines how trade affects the survivability of agents on the landscape and allows for the examination of the percent of different artifacts on the landscape. I examine this model in two steps: 1) a simple model allowing for the exchange of wine for grain; and 2) a model that allows for two types of merchant populations, Etruscans and Greeks, to trade with the Gauls for grain.

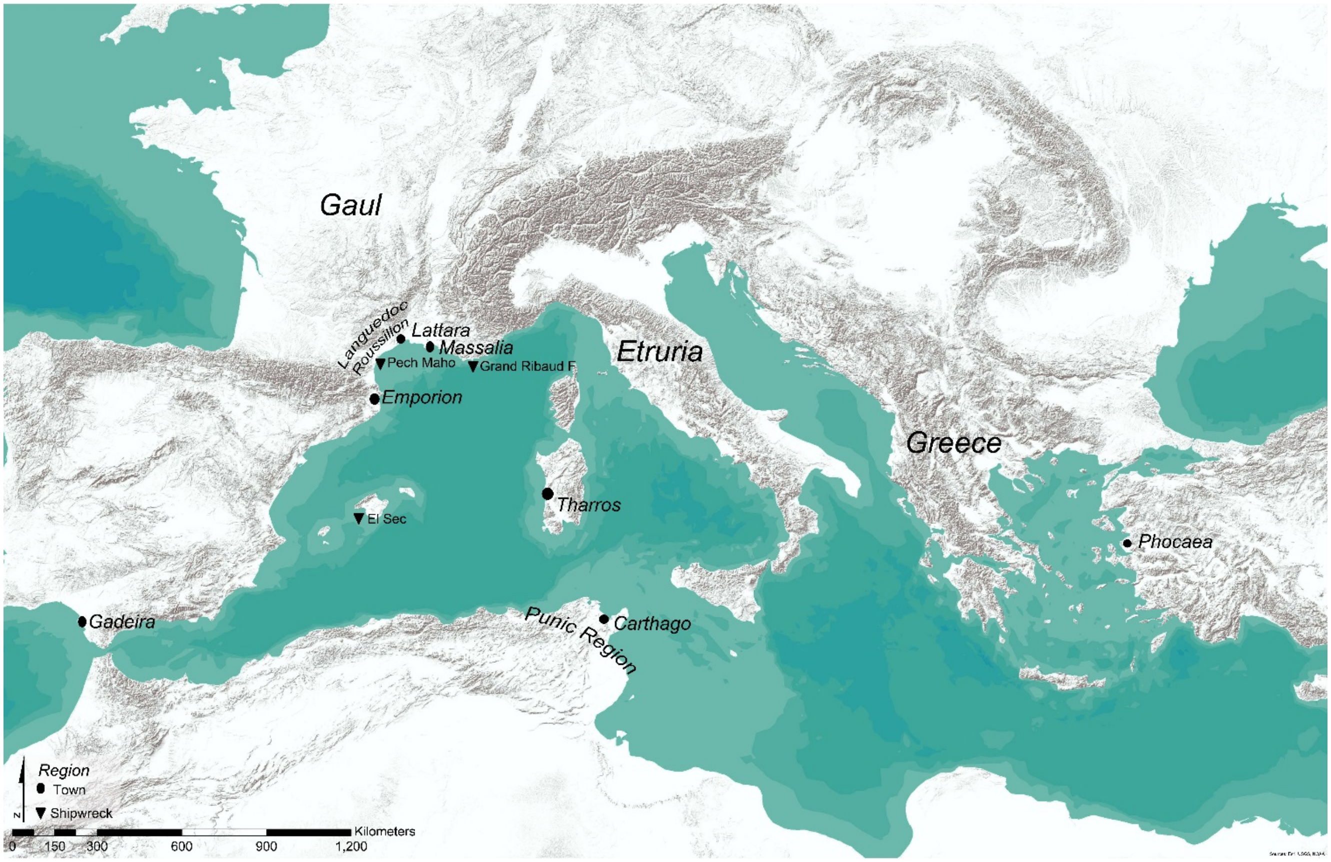


Figure 3.2. Area of interest for this study. This study specifically examines the development of viticulture and trade in the Languedoc Roussillon region, but map includes surrounding areas of interest to this study. Here I show those cities that are specifically mentioned in this manuscript, as well as the three shipwrecks mentioned that show integration of ethnic identities.

1.2 Methods

The agent-based model developed in this paper was created in NetLogo (Willensky 1999), though could have easily been created in any other modeling platform; figures were created in R (R Core Team 2013). The modeling framework consists of a simple resource extraction model coupled with a trade model (see below). Each timestep of the model represents one year and the model is run for 500 timesteps. Two types of output are generated: populations of agents (Gauls and merchants) and populations of artifacts (Etruscan and Greek wine amphorae).

This model is meant to reproduce patterns for validation. While no reliable population estimates exist for this area, patterns of agent survival are helpful in calibrating whether or not exchange of grain for wine would have enabled merchant survival in prehistory. Patterns of artifacts, however, are more reliable in this study area. Output of the quantity of Etruscan and Greek amphorae are compared against real archaeological patterns of artifacts (Figure 3.1) to determine if local processes could have led to the archaeological record.

1.3 The Model

Here I ask two questions: 1) could visiting merchants have survived in the littoral without farming grain? ; and, 2) can a transition in the number and type of amphorae be generated through modifying a simple set of parameters? I examine these questions through the simple agent-based model detailed below. Following I describe the base of the model to provide a background for the questions answered in this paper, then I detail each of the models.

The landscape

The landscape is 80-cells by 80-cells wide, creating a total of 6400 cells for the simulation window. In this model the landscape is created in three portions: the sea to the south (2400 cells), the littoral region abutting the sea (320 cells; light green in Figure 3.3), and the rest of the land (3680 cells; medium green in Figure 3.3). Grain (energy) can only be grown on green patches.

At simulation instantiation a random 33% subset of the farming landscape is unproductive. Regrowth "clocks" are set on each cell randomly between 0 and 60 years and the patches regenerate during this time. While the model presented here does not use realistic paleoproductivity estimates (*sensu* Kohler and Varien 2012), the random generation of unproductive cells creates a patchy environment that farming Gauls likely faced when they began cultivating wheat. As stated above, the conceptual model used by proto-historians (e.g. Py 2012:

135) suggests that Gauls abandoned semi-nomadic pastoralism to create surplus for trade. It is likely that not all Gauls would have abandoned this way of life immediately, suggesting that some parts of the landscape would still be in use for pastoralism and foraging. Moreover, lanscape productivity may have been effected by generations of landscape use before settled farming took hold. Thus it is reasonable to expect that not all of the land was available for farming right away. Further, their actions degrade the landscape (see below) which makes Gaulish agents need to learn to be able to farm, reproduce, and trade.

The decision to abstract the landscape to a rectangular space was made to enable an examination of the simple process of exchange without having to model multiple historical details (Supplementary Figure 3.1). Archaeology and historical study has been ongoing in this region for decades. An agent-based model would not be able to encapsulate all of the specifics of the historical record of this region. Moreover, as this is the first agent-based model to be made in this region, it was determined that it would be best to create a highly simplified model with the goal of adding complexities later.

The agents

There are two main types of agents in this model: Gaulish agents and Merchant agents. In this model, agents correspond to the economic production unit of a household (*sensu* Kohler and Varien 2012). The composition of households may have been slightly different for Gauls than for the Etruscan and Greek visiting merchants, and may have differed depending on social status. For example, on arrival in southern France many of the visiting merchants were likely single men who later may have married locally to create a family or returned home and brought their families from their home countries to the west (Dietler 2010). For simplicity, in this model it is assumed that agents are independent economic production units. As such, each agent produces goods specific for its type: Gauls produce grain, and Etruscans and Greeks produce wine.

In this model households can be of varying size, and this is tied to production (see below). It is assumed here that the basic household may begin with only one agent—for example, when merchants land, a household consists of one merchant. As households increase their grain storage, they can support more individuals. Then, as households fission and split their grain storage, they can support fewer individuals within their own household from their storage. So household size fluctuates as storage fluctuates, and as daughter households bud off of the parent household. This is explored below in the discussion of grain consumption rates.

To examine how the trade of grain for wine helped the survival of visiting merchants, we need to understand consumption rates of grain in the Gaulish world. Gras (1985:95) identified average consumption rates of roughly six hectoliters (*hl*) of grain per year for adults. I use this as a base value for consumption by the agents, with four *hl* of grain as the base for juveniles. In the simulation, if a Gaulish agent has below 10 *hl* of grain, the household can only support one individual. This scales up as agents store more grain (Table 1). Average annual yields of fields have been suggested to be up to eight *hl* per hectare (Dietler 2010: 116), so I use this upper bound to calibrate consumption rates and field productivity in the simulation. To calculate the size of family farms I use estimates by White (1970) who reports that small farms in the Roman republic, which used similar farming techniques, were between 18 and 108 *iugera* or 4.5 to 27 hectares during the 5th century B.C. (contemporaneous to this study). The amount of grain harvested also scales with the size of the family; a small family can harvest from 5 hectares, while a large family can harvest up to 15 hectares. This is explained below in Table 3.1.

Wine cultivation, however, does not scale with a larger family. In this simulation individuals can harvest 10 amphorae of wine per cell and do not create more viticulture cells with increased family size. Rather, an agent owns one cell of wine production. While amphorae in antiquity varied in size, in this simulation I assume that the amphorae are the standard Attic size of roughly 50 liters of wine per transport amphora (Cahill 2002: 332). When I discuss trade rates below, the optimum trade is 40*hl* of grain for 5*hl* (10 amphorae) of wine.

Table 3.1. How storage level affects the number of individuals in a household and their consumption rates. This enables agents to increase their family size, and thus the productivity of their land, as well as increasing the ability to trade. However, once an agent trades, its storage level will be cut in half (as half is donated to the daughter household) decreasing the household size in the process. Merchants have a higher storage level because they cannot grow their own food, and thus need to plan more to be able to raise daughter households.

Storage Level Merchants	Storage Level Gauls	Size of plots Gauls	Size of harvest Gauls	Consumption Rates Gauls and Merchants	Corresponding number of individuals per household
< 45 *hl*	<= 10 *hl*	5 *ha*	40 *hl*	6 *hl*	1
>= 46, <50*hl*	>10, <=30 *hl*	5 x 1.5 (7.5 *ha*)	60 *hl*	12 *hl*	2
>=50, <60*hl*	>=31, <=40 *hl*	5 x 2 (10 *ha*)	80 *hl*	16 *hl*	3
>=61, <70*hl*	>=41, <= 50 *hl*	5 x 2.5 (12.5 *ha*)	100 *hl*	20 *hl*	4
>=71*hl*	>=51 *hl*	5 x 3 (15 *ha*)	120 *hl*	24 *hl*	5

Consumption rates are tied to various parameters, including the basic consumption of grain (6 hectoliters per year, per adult) plus the quantity of grain required for planting and harvesting (see below). While farming yield, amount consumed, and exchange rate are all parameterized, in this run of the simulation these parameters were fixed for simplicity. Fixed parameters are reported in Table 3.2. Of note, planting calories and harvest calories are both set to 4 hectoliters. Gauls would have needed to store seed to plant their fields each year, and planting would be energetically costly. Thus the parameter "planting calories" encapsulates both the stored grain, and the cost to plant a large field. Harvests, on the other hand, are known to come in at once and need to be harvested rapidly before the grain falls off the stalk. Thus Gauls likely relied on neighbors (and potentially slaves, see Discussion) to help with harvest, and may have fed them to help with this cost. Further, some grain that grew may be lost in harvest, due to improper techniques, harvesting too late, or storing improperly. Thus "harvest" encapsulates the costs associated with harvest and storage. Swept parameters are reported in Table 3.3.

Table 3.2. Fixed parameters used in this simulation. Many of these were tested in earlier sweeps, which are not reported here.

Parameter Name	Value	Explanation
Grain Storage (Gauls at birth)	20 *hl*	Amount of grain per Gaul when seeded on landscape
Grain Storage (Merchants at arrival)	60 *hl*	Amount of grain per merchant when seeded on landscape
Wine Storage (Merchants at arrival)	20 amphora	Amount of wine per merchant when seeded on landscape
Number Gauls Seeded	150	Number of Gauls at start of simulation
Number merchants seeded (both types)	100	Number of merchants upon arrival
Life expectancy	80	Year after which agent has 50% probability of mortality per timestep
Etruscan arrival	Year 34	Year Etruscans arrive
Greek arrival	Year 100	Year Greeks arrive
Grain harvest amount	20	Amount of grain (in hectoliters) harvested per farmed cell
Wine harvest amount	10	Amount of wine (in amphora) harvested per cultivated cell
Planting calories	4 *hl*	How much it costs to plant each year
Harvest calories	4 *hl*	How much it costs to harvest each year
Wine decay rate	1 amphora/yr	How much wine rots per year
Wine drinking rate	1 amphora/yr	How much wine an agent can consume per year, per type
Reproduction	3%	Probability of reproduction per timestep
Probability of selling wine (merchants)	5%	Probability a merchant will be able to sell wine each time step
Probability of buying wine (Gauls)	1%	Probability a colonist will be able to buy wine each time step

Table 3.3. Parameters swept across in two models. Grain Trade Rate was swept across in first model. Preference was swept across in second model.

Parameter Name	Values Swept Across	Explanation
Grain Trade Rate (examined in part 2.1)	20:10; 30:10; 40:10; 50:10, 60:10	Amount of hectoliters of grain traded per 10 amphorae of wine
Preference (examined in part 2.2)	0, 10, 20, 30, 40, 50, 60, 70, 80, 90, 100	Weighted value for when two types of wine are available. Explained further in Table 3.3

At the beginning of the simulation—here set to year 0, but corresponding to roughly year 700 B.C.—Gaulish agents are distributed randomly on the land portion of the landscape. Each Gaulish agent is created with a storage of grain set to 20 hectoliters. The initial number of Gaulish households is set to 150. Colonist agents are seeded on the landscape during their birth years (Table 3.2) with 60 *hl* of grain in storage, and the initial number of colonists is set to 100.

In this model agents have yearly basic metabolic needs which are met by consuming grain (Table 3.1). If agents get to zero energy, they die. There is an additional parameter, "life expectancy," that ensures agents—the natal household—do not live too long. If an agent reaches above the number of timesteps set by "life-expectancy" they have a 50% chance of dying every timestep. (Note that agents can die before that due to lack of resources.) In this sweep life expectancy was set to 80 timesteps since birth; while this is likely a high estimate for antiquity, this allowed many agents to die of "natural" causes (e.g. having too few grain) before being killed off by the simulation. Reproduction in this model is via fission (see Supplementary materials). Daughter households form near their parent household, and storage is divided evenly between daughter and parent households.

Consuming wine decreases harvest costs (and is consumed at a rate of one unit per year). Elsewhere, beer parties are used as a form of payment to help in collective labor (e.g. McAllister

2006). Alcohol mobilizes workers at work-parties, and was likely used in Gaul for harvest, since crops would mature and need to be harvested quickly. Historians have suggested that beer parties indeed aided in Gaulish grain harvest (Dietler 1990: 365). For this simulation I apply the concept of beer parties and assume that consuming wine would decrease costs to the harvester. Therefore, having wine is beneficial for farming agents, as it makes harvesting less costly for them.

Agents trade wine for grain, and trade is costly. Both the wine and grain traded would need to be transported between exchanging agents, so agents are charged calories for the trade of these goods across the simulation in a manner similar to Crabtree (2015). Further, wine was likely an elite drink, and so the trade of grain for wine could only be accomplished by the elite. Thus, agents must account for costs when trading. In this model agents calculate the distance between themselves and their trading partner. The agent that is buying is charged 0.25 *hl* per cell traveled. This, then, ties to the agent's move algorithm.

In this model cells degrade after 5 years of farming use; cells become productive again after up to 5 years lying fallow, set randomly. If a Gaulish agent's farm cell has become unproductive, the agent must move to another cell. When Gauls move, they will look at its most recent trading costs and assess how costly they were. If the trading costs were greater than ¼ of the gain in storage, the agent will move to a productive cell closer to the merchant settlements. If the costs were less than ¼ of the agent's grain storage, the agent will simply look for another productive cell in a radius of 10 cells to begin a new farm. The Gaulish agent is charged 1 *hl* to move to a new farm.

Trade in this model is simple, but occurs both from the Gaulish side and from the Merchant side (see Supplementary Material: ODD Protocol, Scheduling). Gaulish agents trade before merchant agents do (demand for goods comes first). When Gaulish agents have stored twice the trade rate in the simulation (in section 2.2 set to 40*hl*) they may choose to trade for wine. This threshold is so that if an agent reproduces (dividing energy equally) it will have 40 energy to divide between itself and offspring after trading energy for wine; this threshold minimizes agent-death. Merchant agents require grain to survive and reproduce; thus a merchant will always trade for grain when approached by a Gaulish agent asking for wine. The agent that instantiates trade pays the cost for trading as described above (*sensu* Crabtree 2015). After Gaulish agents trade and complete their scheduling, merchant agents trade.

Second, merchant agents trade wine for grain. When colonist agents have greater than 10 wine-units, they ask a Gaulish agent to trade following the above logic. The merchant agent asks a Gaulish agent to trade; the Gaulish agent then has a 50% probability of accepting this trade. If the trade is accepted, the merchant agent pays the cost of trading (0.25 energy multiplied by the number of cells separating it from the Gaulish agent).

Following I now describe the differences in each model, building from the simplest base model that examines the trade of grain for wine with one type of merchant-agent, to the more complicated model that examines the trade of two types of wine for grain. I additionally discuss the results from running sweeps of each model-type.

2. Results

2.1. Base Model

In this section I use the base model to establish the trade rate of grain to wine to be used in the subsequent model. While future applications of this model may enable agents to barter for an appropriate trade rate (*sensu* Cockburn et al 2013), this model sought to reduce variables, so a global exchange rate was determined in this first step. This model examines the verbal model as explained by Py (1990), that Etruscan merchants arrived in Gaul and influenced an intensification of agriculture in the area, with Gaulish people creating surplus to engage in trade for wine with the Etruscans. Here I specifically examine population of Etruscan agents, since their survival depends on their ability to trade with Gaulish agents. In this model I calibrate the amount of grain traded, which then feeds into the following models. For this model I specifically ask:

> Could Gauls have generated enough surplus to feed visiting merchants, while still enabling their own survival?

Here only farming Gauls and Etruscan merchants exist, so only grain (energy) and one type of wine are traded.

Five exchange rate values were examined (Table 3.2): a rate of 2:1, 3:1, 4:1, 5:1, and 6:1. Value of 1:1 and 7:1 were examined; at 1:1, Etruscan merchants died out quickly (as they do in 2:1), while at 7:1 Gaulish agents died out quickly, which caused the simulation to stop. The basal amount of trade each year is 10 amphorae of wine, so the amount of grain scales accordingly (e.g. 40:10, which equals 40*hl* of grain for 5*hl* of wine). In summary, colonist agents cannot survive unless they trade wine for grain. Figure 3.3 reports the response of population to these trade values.

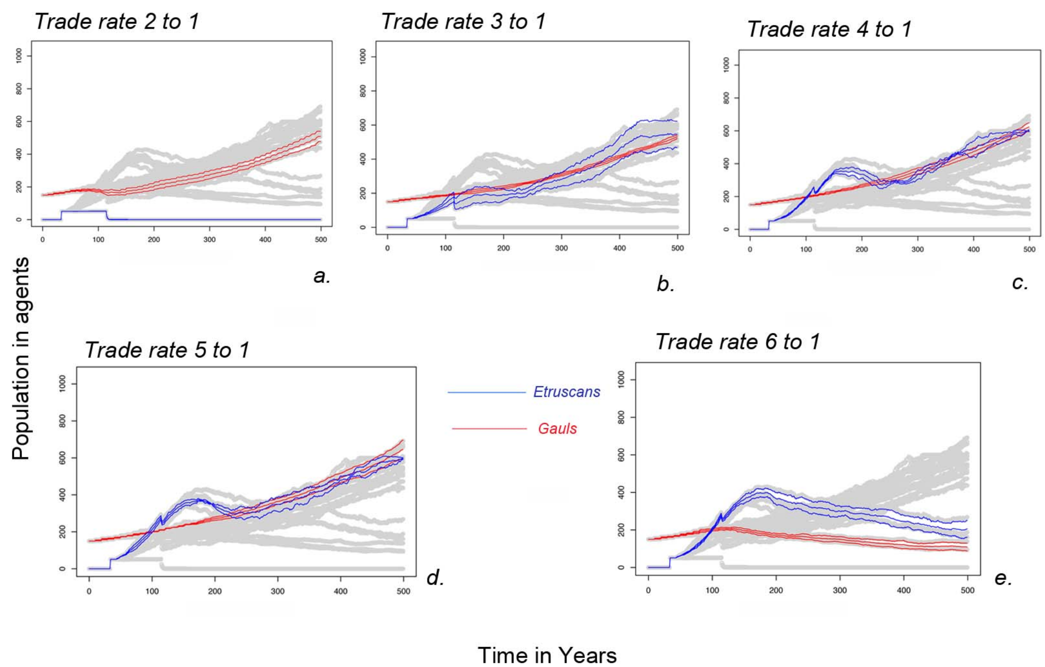


Figure 3.3. Population response in the simulation, tied to the consumption of grain (grey lines). Solid lines denote the mean population for the scenario being examined, dotted lines denote one standard deviation of the mean above and below the mean. Scenarios a through e represented different trade rates examined in this simulation.

In (a) I examine the trade of 20 hectoliters of grain for 10 amphorae of wine. Note that merchant-agents die out almost immediately. In (b) the trade rate (3:1) is more favorable to merchant populations, and their population trajectory reflects this. Note there is large variance around the mean. In (c) the trade rate (4:1) is increasingly favorable for merchant populations, with their population trajectories more-or-less overlapping by year 300. In (d) the trade rate (5:1) is again favorable to merchant populations, and the two population trajectories have significant overlap, as with (c). However, the variance around the mean is larger in (d) than (c). In (e) Gaulish agent populations begin to die out due to the unfavorable trade rate (6:1). This may reflect the trade-rates that some merchants attempted to achieve reported by Diodorus Siculus (1939). This poor trade rate negatively effects merchant populations as well; with fewer Gauls to trade with, the quantity of available grain diminishes, decreasing merchant population.

While many of the trade rates examined here would have enabled the survival of merchant populations in southern France, a trade rate of 40*hl* of grain for 5*hl* of wine (4:1) creates a favorable exchange rate for both merchant and Gaulish populations, while reducing variance around the mean (reducing path dependence). Thus a trade rate of 4:1 was set for the subsequent models examined in this paper.

Though this model is highly simplified, by using historically reported yield rates (8*hl* of grain per hectare, with family farms from 4.5 to 27 hectares, consumption of 6*hl* of grain annually per adult, and 4*hl* per child, 50*l* of wine per amphora) it shows that Gauls would have been able to grow enough grain to support themselves and a burgeoning economy. This has important ramifications, and will be discussed below (Discussion). Using these historical rates reported above for average field productivity and average farm size, it is completely feasible that a household would be able to produce enough grain for immediate consumption, storage, and trade. Then, through the trade of wine for grain, merchant populations were able to reproduce and grow their numbers, establishing colonies along the littoral, and engaging in long-term trade with Gaulish farmers. This model verifies Py's first hypothesis (1990). Next, I build on this simple model to examine how the inclusion of two different types of merchant populations effects the distribution of artifact types across the landscape, and the survivability of each type of agent.

2.2 Multiple-colonist Model

At the beginning of this article I quote Eco, who illustrates the preference of one type of wine for another. While Eco writes of 12th century Italy, the preference for red wines from Etruria, or for wines that are "bitter" and "tasting of mold" would have governed purchasing tactics by prehistoric consumers. In this second simple model I show how these preferences create distinctive artifact patternings that can then be compared to real archaeological data. The model presented in this section builds on the simple trade model presented in section 2.1. In this model Gaulish agents choose to trade for either Etruscan or Greek wine.

Gaulish agents will favor buying wine according to the parameter, “preference.” Preference governs the choice between Etruscan and Greek wine, weighting the probability of choosing a Gaulish or Etruscan wine depending on the perceived value by Gauls. Of course, before Greek agents arrive, Gaulish agents will only purchase Etruscan wine, and thus preference has no effect. Preference can take many forms. Preference could be for the taste of the wine, the rarity of it (causing it to have higher prestige status), or in mimicking the elite (Hashim et al 2004). When preference is set to 50, Gaulish agents have a 50% chance of choosing Etruscan or Greek wine (they don’t prefer either, they just want wine). The closer the value is to 0, the more weighted it is in favor of Etruscans, while the closer it is to 100 the more weighted it is in favor of Greeks. These are explained below in Table 3.4.

Table 3.4. Preference Values swept across in this study.

Preference	Explanation
0	Weight is entirely in favor of Etruscan Wine
10	Weight is strongly in favor of Etruscan Wine
20	Weight is in favor of Etruscan Wine
30	Weight is slightly in favor of Etruscan Wine
40	Weight is very slightly in favor of Etruscan Wine
50	There is no weighted preference between Greek or Etruscan wine.

60	Weight is very slightly in favor of Greek wine.
70	Weight is slightly in favor of Greek wine.
80	Weight is in favor of Greek wine.
90	Weight is strongly in favor of Greek wine.
100	Weight is entirely in favor of Greek wine.

Eleven preference values were swept across (reported in Tables 3.3 and 3.4) to examine how a simple change of preference could influence both the survival of agents on the landscape and the artifact assemblage across the landscape. Each of these models was run for a total 30 runs per preference value, creating a sweep of 330 runs. Results are reported in Figures 3.4-5. In these figures the average population per each preference value is reported along the left column while the average number of artifacts of each type through time is reported along the right column; solid lines indicate the mean of all runs, while the dotted lines indicate the high and low standard deviations around the mean. It should be noted, however, that even though Gaulish agents may prefer one type of wine over the other when they initiate purchase, each merchant agent initiates trade with a Gaulish agent after the Gaulish agent has finished its scheduling (see Supplementary Information). The Gaulish agent then has a 50% chance of choosing to trade with the merchant or not. Thus, while preference should affect the results, it should not completely control the assemblage types, and even when Gaulish agents prefer one type of wine over another, due to the logic in this simulation, merchant agents should be able to survive, albeit in low numbers, since merchants can initiate trade as well.

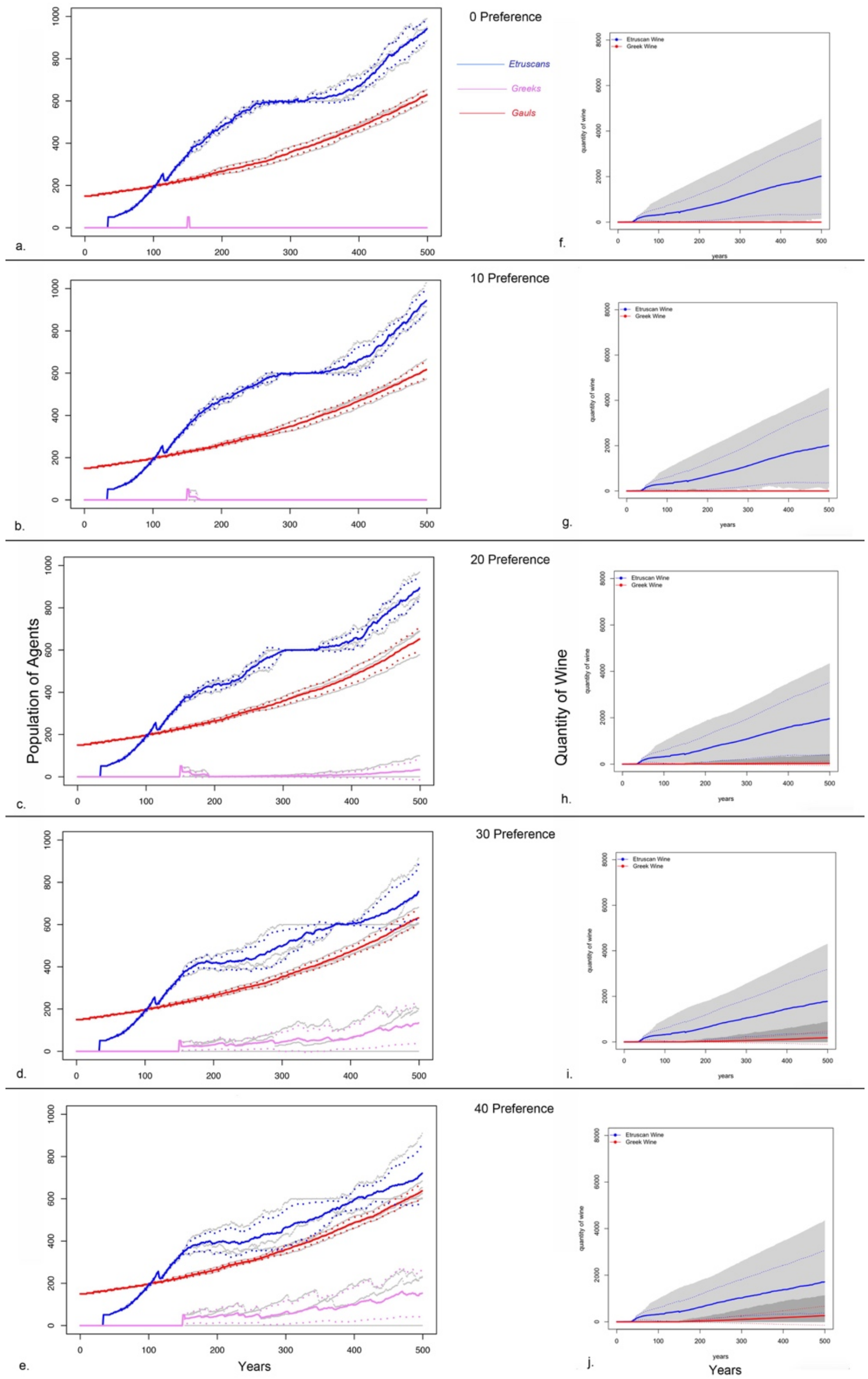


Figure 3.4. Response of population and artifact type based on preference value, beginning with a preference of 0 (in favor of Etruscans) and ending at a preference value of 40 (almost equal preference, still in favor of Etruscans). Preference values are reported in the middle of each tile, corresponding to the values on the left and the right. Left side of tiled figure corresponds to population, while the right side corresponds to the artifact assemblage. Solid colored lines denote the mean, while dotted colored lines denote one standard deviation above and below the mean. Grey lines indicate overall variation of output in simulations.

In Figure 3.4, preference is set initially so that Gaulish agents prefer Etruscan wine (preference 0, Figures 3.4a and 3.4f). In this model, Greek agents have difficulty establishing trade relationships with native Gauls (Figure 3.4f) and die out essentially upon arrival (Figure 3.4a). The same occurs when preference is set to 10 (Figures 3.4b and 3.4g); when preference is set to 20, Greek agents survive slightly longer, but still die out (Figures 3.4c and 3.4h). This type of situation may be expected when a strong economic partnership develops between two entities, making it difficult, if not impossible, for a new competitor to enter the market. The new goods may be seen as "strange" (e.g. they may "taste of mold") and thus not desirable. Moreover, the new product may not offer anything better than the older products, and the lack of a relationship between the new sellers and the buyers may influence the sale of those products (Mazzeo 2002).

As we move down preference values in Figure 3.4, Greek agents are able to survive easier as the preference value approaches 40%. Yet even in Figure 3.4e the population of Etruscans holds strong even after Greek agents arrive. In Figure 3.4j it is evident that the slight preference for Etruscan wine over Greek wine influences the distribution of artifacts so that Etruscan amphorae are more prevalent.

In the next set of tiled figures, response of population when preference is set at 50% is examined (Figure 3.5a and 3.5g). When Gauls weight Etruscan and Greek wine evenly, both Etruscan and Greek wine are present. However, since Etruscans arrive sooner in this simulation (during year 34) they have a longer time to establish trade relationships with Gauls and reproduce along the littoral. Thus, when Greek agents arrive, Etruscan agents outnumber them. The low proportion of Greek wine in the assemblage shows that, while Greek merchants can (and do) trade wine for grain, the quantity reflects the challenge for Greek merchants to gain a foothold in the region.

When preference values begin to favor Greek merchants (Figures 3.5b and 3.5h) the average number of Etruscan agents and Greek agents stays similar, yet because Etruscans were on the landscape longer they maintain the majority of amphorae (Figure 3.5h). Only when preference reaches a value of 80, and Greek agents dramatically outpace Etruscan agents (Figure 3.5d) do the mean number of Greek amphorae begin to be more numerous than Etruscan amphorae (Figure 3.5j). When preference is set to a value of 90, the mean number of Etruscan amphorae levels out (Figure 3.5k) showing that the growth of grapes and trade of wine is at a strict replacement rate for the amphorae that are being discarded. Finally, when preference values are set to 100, we see both Etruscan population dying out (Figure 3.5f) and attrition of Etruscan vessels decrease their presence in the simulated assemblage (Figure 3.5l).

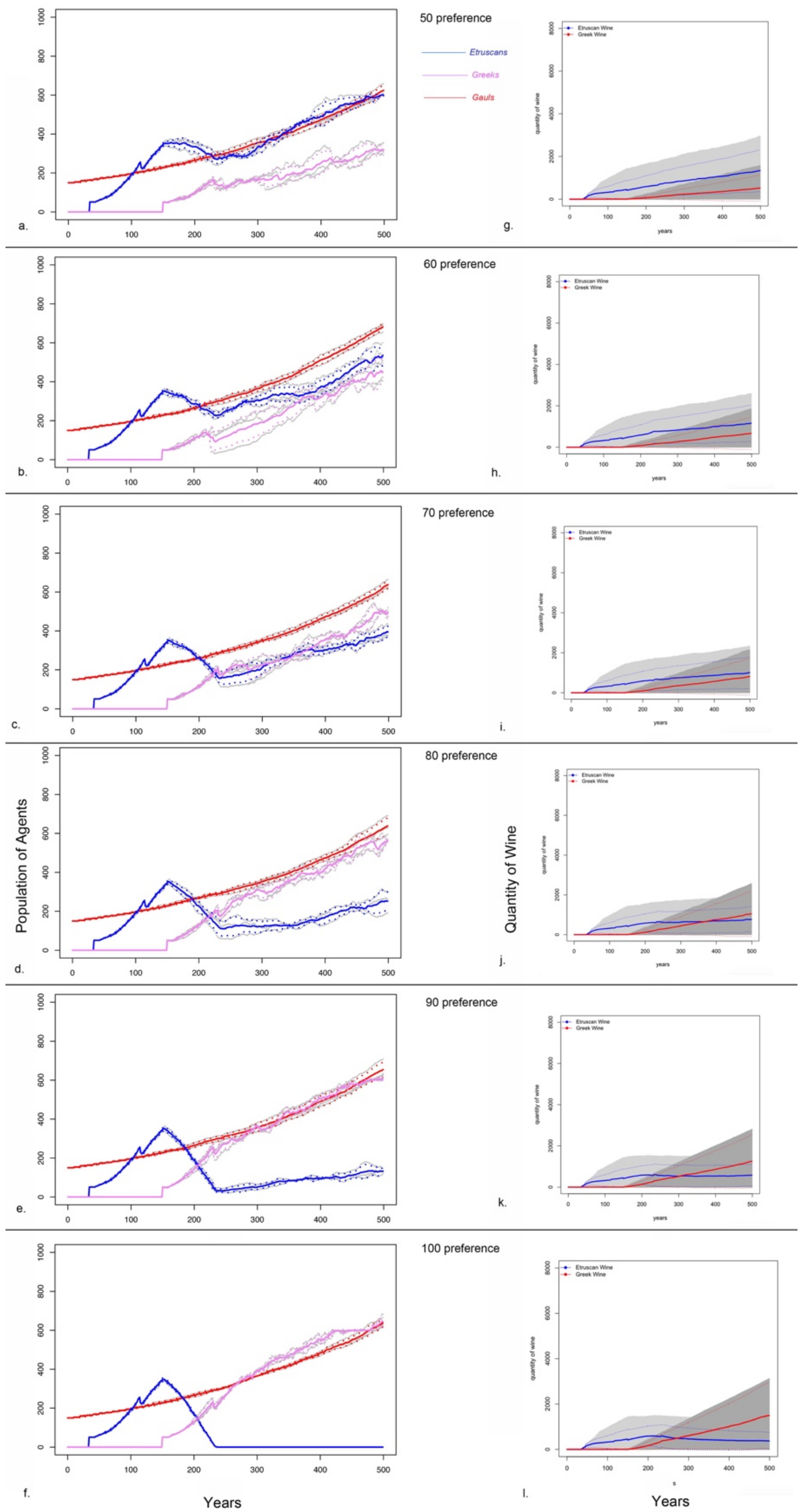


Figure 3.5. Response of population and artifact type based on preference value, beginning at preference of 50 (no preference for Greek or Etruscan wine) and ending at 100 (preference for Greek wine). Preference values are reported in the middle of each tile, corresponding to the values on the left and the right. Left side of tiled figure corresponds to population, while the right side corresponds to the artifact assemblage. Solid colored lines denote the mean, while dotted colored lines denote one standard deviation above and below the mean. Grey lines indicate overall variation of output in simulations.

In Figures 3.4 and 3.5 each of the 11 preference values is displayed, demonstrating how preference affects both the distribution of artifacts on the landscape and the survival of each of the agents types on the landscape. Here a phase transition at preference value 30 is evident, after which Greek agents are able to survive and trade. Below this value it is difficult for Greek agents to survive since Gaulish agents have a strong preference for Etruscan wine. Further, since Etruscans arrive first on the landscape, they are able to monopolize the market and establish their own territories.

The next phase transition occurs at a preference value of 70 (Figure 3.5b and 3.5h) where the mean quantity of Greek wine begins to approach that of Etruscan wine by year 400 (Figure 3.5i); in this scenario the mean population of both Etruscans and Greeks is quite similar from year 250 onward. Then, when preference values are set to 80 and 90 Greeks do well, yet Etruscans do not die out. While their populations diminish, they still exist. This is in stark contrast to when preference was set to 10 or 20; in those scenarios, since Etruscans had already established a monopoly on the economy, Greeks were unable to trade enough (or quickly enough) to reproduce. When preference values are set to 80 and 90, in contrast, Etruscans have already lived on the landscape long enough to create storage and establish trade relationships with the Gauls. They can weather a few years of bad trade relationships due to their longevity in the region. It is only when a preference value of 100 is used that Etruscan merchants completely die out. Indeed, their die off is precipitous and complete by year 250 (Figure 3.5f).

When Figures 3.4 and 3.5 are compared to Figure 3.1, we can see that it is Figures 3.5j, 3.5k, and 3.5l that most closely resemble Figure 3.1; when Gauls "prefer" Greek wine, Greek wine amphorae begin to outnumber Etruscan amphorae even though Etruscans can still trade wine for grain. While it should be noted that the consumption/decay rate built into the simulation decreases the amphorae at a rate of 1 amphora per agent per year, these rates likely reflect use (and discard) in prehistory. Many amphorae were reused, yet many more were recycled when they became cracked or chipped (or perhaps even unfashionable).

Prehistoric France was littered with amphora sherds, and not necessarily because of the ravages of time. (Indeed, modern France is still littered with these amphora sherds). Instead, archaeological evidence suggests that humans who lived during the time examined here (~700 B.C. to ~100 B.C.) recycled amphorae as paving gravel, as chips for building walls, as fill for creating land (such as building an artificial hill), or as roof tiles for buildings (Twede 2002). If objects were cherished, they would be preserved; consequently, we should see those objects lasting for generations in the archaeological record. Yet if objects are not cherished, and instead are utilitarian, utilitarian objects that outlasted their utility (or became unfashionable) would be discarded. In the simulation amphorae are discarded when the wine is drunk, but also there is no inheritance when an agent dies. Consequently, when an agent dies all of its amphorae are discarded (metaphorically recycled into roof tiles or paving sherds). Thus the new generation will drive the demand for certain types of amphorae due to the practicality of recycling. The artifact curves examined in Figure 3.1, and recreated in Figures 3.5j, 3.5k, and 3.5l, reflect an evolving preference by Gaulish consumers for Greek wine.

However, even though Greek wine replaces Etruscan wine in the simulation, the discard rate of Etruscan sherds in Figures 3.5j, 3.5k, and 3.5l is much slower than in Figure 3.1. This suggests that the use and discard rate in prehistory is much faster than what was used in the simulation. In reality, Etruscan amphorae were used and discarded quickly, suggesting that these amphorae were not treasured objects, but utilitarian vessels that had more use when recycled than being reused in their original form.

This pattern—of a replacement of one type of amphora by another—has been mystifying archaeologists in this region for decades. The model presented here provides a way forward to examine how Gauls drove the economy, and created the archaeological assemblage seen today by their preference for one type of wine over another. Thus, pattern oriented modeling, where I sought to create a virtual artifact assemblage through simple rules of exchange, helps to illuminate the complex processes of prehistoric decision-making and prehistoric economies. Further, as will be discussed below, while archaeologists can identify the amphora, the objects the amphorae were traded *for* are missing. This model proves that merchant agents, if they did not engage in farming practices (which was likely, see below) could trade local farmers for grain, and through this trade they could survive along the littoral. Thus through creating patterns of artifacts, and examining how the trade of grain for wine effects the survival of merchant agents, I conclude that Gauls drove the economy, but their desire for luxury wine and their willingness to farm enough grain for trade enabled the survival of merchant agents (both Eturscan and Greek) along the littoral.

Of interest, however, is the fact that Etruscan merchants do not die out in Figures 3.5d and 5e. Rather, they persist until the end of the simulation. This is explored below with archaeological data on the persistence of different ethic identities of merchants well into the Iron Age in Southern France.

3. Discussion

When an entity creates a monopoly on a type of good, a dramatic and complete switch to another type of that good is suspect. From archaeological data what is clear is that Etruscan amphorae become replaced by Greek amphorae in a rapid amount of time. In the following data (section 3.2, *Trade with Outsiders*) I suggest that this is not because Etruscan merchants were not present along the littoral. Rather, Etruscans *were* present, and their wares were represented *alongside* those brought by Greek merchants. If these were both present, how would one dominant type of amphora become completely replaced by another?

If one artifact type is technologically superior it may gain a higher quantity of the market share; it may be tempting to suggest that Greek wine, or at least Greek amphorae, were superior. However, it is not necessarily always the case that a technologically superior good will become dominant. Technologically superior goods can be expensive, and if other more readily accessible goods are still at hand, replacement makes little sense. Rather I suggest that it is the *desire* for a different type of material that creates the switch. Otherwise, both should be present, since some individuals will continue to use (consume) the older material.

In the above model I show phase transitions at 30% and 80%. Here, it is not necessary for 100% of Gauls to prefer one type of wine over another. Rather, when an individual prefers Greek wine 1 out of every 5 times, Grecian merchants are able to stake a stronghold along the littoral. Thus, this model demonstrates that it is not necessary for 100% of the populace to prefer buying one type of wine over another, but rather that critical transitions happen at percentages much less than 100%.

Further, recall that these results are for the demand side. Etruscan and Greek merchants can still approach Gaulish agents and ask to sell. While Gauls will only accept buying 50% of the time when they are approached, even then this pattern of complete artifact replacement is present. This shows how important the demand side is for the supply-demand chain of Gaulish consumption (discussed further below) and demonstrates the agency Gauls had in shaping their economies.

3.1 Archaeological evidence: Mixing of Colonial Entities

Modern conceptions of nationalist trade ventures likely do not hold for trading in antiquity; Greek and Etruscan merchants likely coexisted and traded each others' wares. This is evident in recovered vessels from shipwrecks. De Hoz (1987) notes that the El Sec shipwreck (Figure 3.2), dating to the 4th century B.C., contained a vast array of types of amphorae, 30 percent of which came from Samos (Figure 3.2), with Punic and Greek graffiti present on the recovered vessels (De Hoz 1987; Koehler 1989: 132). This mixing is present in other contexts, such as the Grand Ribaud F shipwreck (Figure 3.2) where Etruscan and Greek goods are both represented (Rouillard 1991), and on a lead tablet inscribed with both Greek and Etruscan text, recovered at Pech Maho in western Languedoc (Figure 3.2 [Chadwick 1990; Dietler 2010: 141]). The replacement of amphorae from Etruscan-type to Greek-type does not necessarily mean that ethnically identified Etruscans were no longer present in Gaul, or that Etruscans were no longer producing goods to trade. The replacement rather indicates that there was a cultural shift from wanting Etruscan wine vessels to wanting Greek wine vessels, and likely the contents within them, too. Etruscans and Greeks were present simultaneously, yet vessel-type changed rapidly. Understanding Gauls as drivers of the economy may help illuminate the transition to Roman amphorae that occurred much later (Figure 3.1).

3.2 Trade with Outsiders

The Gaulish littoral was not isolated, but had contact with traders well before the development of the complex exchange networks noted archaeologically. For example, Punic traders interacted with Gauls in the Languedoc since at least the 8th century B.C. (Py 2012: 46; Villard 1960: 87). However, these interactions were short and established no high-intensity trade relationships. Objects of Punic origin, including amphorae, vases, and glass objects are present in Gaul beginning in the 7th century B.C. However, no evidence for Punic settlement is present. While

Punic boats likely made frequent trips across the Mediterranean to Languedoc (Py 2012), these interactions left ephemeral traces. Further, Villard (1960:75-77) notes that Gauls in a small settlement in what would become Massalia likely had contact with merchants from Phocaea, an Ionian Greek city on the western coast of Anatolia, a half century before the founding of Massalia as a Greek city (contemporary Marseille, see Figure 3.2; Villard (1960: 78) places the foundation of Massalia between 600 and 596 B.C.)

Ceramics for the transportation and drinking of wine arrive in southern Gaul by the late seventh century B.C. These ceramics are composed primarily of Etruscan wine amphorae, although Etruscan *bucchero nero* pottery, as well as a small quantity of Greek ceramics (likely imported by Etruscans) are also present (Villard notes roughly 30 of these in Marseille[1960:17]).

Once Massalia was founded, locally produced fine-wares called "Pseudo-Ionian" and "Grey Monochrome" began to be produced (although Villard remarks that the massaliote and imported ceramics are fundamentally the same, just made in different areas [Villard 1960:58]). Some of these wares were traded to indigenous peoples. Villard (1960:58-65) finds a wider range of fine-ware ceramic vessels in Massalia than in indigenous settlements; it appears that ceramics at indigenous sites include only wine-related vessels to complement indigenous bowl forms, while in Massalia ceramics take on more numerous forms. Additionally, wine begins being produced locally in the littoral, such as at Massalia by Greeks (McGovern et al 2013). After c. 525 B.C., local imports of Etruscan amphorae fell off sharply as Massalian-produced amphorae replaced them (McGovern et al 2013). However, Villard also notes that the imported amphorae from Greece are much more abundant in Massalia than locally made amphorae, postulating that "imported wine was more or less consumed where it arrived, even while locally grown and produced wine was largely exported [locally] into the indigenous market" (1960:64; my translation).

Thus, the pattern of trade between Gauls and visiting nonlocal merchants shows that Gauls received almost exclusively pottery related to drinking wine. These included amphorae and wine-drinking apparatus. Yet ceramic assemblages from other areas that traded with Etruscan and Greek merchants show a higher diversity of objects. If Gauls drove the demand for Greek wine, we may be able to expect to see in the archaeological record evidence for Gauls driving other areas of their economy. This is examined below.

3.3 Supply and demand

Morel (1981:484) states that contemporary trade between Etruscans and North Africans does not follow the same pattern as that between Etruscans and Gauls. Rather, southern Gaul's limited type of imports likely reflects consumer demand more than the range of artifacts available. Specifically, the artifact type "amphorette," a ceramic object used for storing high quality wines less than half the size of an amphora (Vallat and Cabanais 2009), makes up approximately half of the *bucchero nero* pottery in Carthage, almost 100% of pottery in Tharros (a city on the western coast of Sardinia, see Figure 3.2), but is "practically inexistent" in Gaul (Morel 1981:485-486). Table wine and wine amphorae are the objects the Gauls desired and do not reflect the variety of objects offered for trade by the Etruscans; rather the makeup of Gaulish assemblages reflect a cultural preference for drinking materials. As Dietler (1990:381) states, Gauls "avidly adopted this foreign form of drink while at the same time rejecting other cultural borrowings."

The trade of amphorae seems to be one-way—evidence for Gaulish products in merchant settlements is thin—so secondary measures for identifying the goods traded are often used. For example, historians suggest that Massalia was so large it would have outstripped its local carrying capacity, and only through trade were inhabitants of Massalia able to eat (Dietler 2010:117).

Coupling this with primary sources, such as Strabo (1923) who describes Massalian land as too poor to produce grain, and the suggestion that Etruscan and Greek traders would not have engaged in subsistence farming due to it being seen as below their station (Wood 1983), grain was likely produced by Gauls and traded to settled merchants. However, this statement had never been tested formally. The model presented above illustrates how the trade of grain could have enabled merchant survival. Further evidence of ships bearing large quantities of grain are recorded as arriving in Greek and Etruscan homelands, and this grain likely came from Gaul (Dietler 2010).

Metal and salt are two other commodities likely to have originated in Gaul and traded to settled merchants. Copper, gold, iron, tin and silver are all found within France, and sources for these are noted in antiquity (Briggs 2003). These metals would have been essential for the creation of objects during the Iron Age, and salt would have been essential for food preservation. Overland transalpine exchange of metals and salts from Gaul to northern Italy began in the early Bronze Age (Briggs 2003:251), so it is likely that Etruscan traders knew that minerals could be obtained in Gaul, thus influencing their decision to trade in Gaul.

As suggested above in discussion of harvest (Section 2.2), enslaved people were likely present along the littoral. Briggs (2003) suggests that Etruscans commonly used enslaved people as servants, and that women and children especially would have been brought to the colonizer homeland as household slaves (Briggs 2003:248-249). While "one of the most elusive of all prehistoric objects of exchange is human labour" (Briggs 2003:248), the importance of slaves in Etruscan households may suggest that Gaulish women and children were some of the "objects" that enabled the trade system to function (Briggs 2003; Dietler 2010). Indeed Diodorus Siculus (1939) writes that some brazen merchants would attempt exchanging one amphora of wine for one slave. (Though this anecdote relates to the first century BC, and this exchange value was likely not the norm.)

So, while wine amphorae are plentiful in Gaulish settlements (Py 1990), the objects for which they were traded remain elusive. Indirect evidence suggests that grain, metals, salt, and slaves were traded to the settled merchants. The model presented above intervenes in these debates. While the objects that were traded may be invisible, the survival of merchants along the littoral suggests that they were able to trade their goods for foodstuffs. This model shows that a simple economic model can enable merchant survival, and can lead to distinctive artifact patterns. While this model is highly simplified, it enables a first step into using agent-based modeling in Southern France, and will be expanded upon the in future to examine expanded economies (such as the trade of metal or salt) and the aggregation of Gauls into oppida.

4. Future Directions

I began this article by proposing that a simple preference for one type of wine over another could cause the empirical artifact distribution recognized by Py (1990) and reported in Figure 3.1. To do that, historically-based farming production rates were employed on a simplified landscape to enable the intensification of agriculture and the trade of surplus wine for grain. In this we can examine landscape use in antiquity and see how it could lead to the establishment of complex economies in the past.

Results in this model showed that when Gaulish agents did not prefer one type of wine over another (when preference was set to 50%) that both Etruscan and Greek wine were present in the simulation, but that Etruscan wine was more common due to being present in the area longer. When preference was set to 20 (Table 3.4) or below it was very difficult for Greek merchants to trade wine for grain and to exist on the landscape. Additionally, when preference was set to 70 or higher (Table 3.4), Greek wine supplanted Etruscan wine as the more common type in the simulation (after Greek merchant arrival). However, it was only when preference was set to a value of 100 that Etruscan died off. Even when this occurred, however, Etruscan wine amphorae were still present for the remainder of the simulation due to a slow use and decay rate.

These findings have important implications for the archaeological record. First, these results suggest that when Greek merchants arrived in southern Gaul that their product was found as desirable. If it was not, the archaeological record may reflect those results in Figure 3.4f, 3.4g and 3.4h. Instead, Figure 3.1 resembles most closely Figure 3.5i, 3.5j and 3.5k, where Greek wine arrived and became common along the littoral. In these figures Etruscan amphorae make up the early assemblage, but are quickly supplanted by a second type of amphora. In the simulation, not only were Greek wines seen as desirable, but upon their arrival they were preferred by Gauls and became the largest part of the assemblage. However, these results also suggest that artifacts can have a long uselife. Archaeological assemblages may not reflect the presence of a population, but may reflect instead the storage and use of those artifacts after a population moves on.

The work begun here is ongoing, as this simple model was a first step in establishing an agent-based model for the development of colonial interactions in southern France. As mentioned above, multiple other types of resources besides grain were traded for wine. While these scenarios are not examined in this publication, this model is being developed to enable the trade of two types of wine for two types of resources—grain and metal. Future research will examine how the incorporation of diverse resources effects the survival of agents on the landscape and the distribution of materials on the landscape. Research is also being pursued into using realistic GIS dataplanes in the simulation, instead of using a simple patchy and regenerating landscape, as was used in the model presented here. This will enable the development of aggregation models based on least-cost path analysis to help agents trade resources across the landscape and establish settlements at optimal locations to enable trade.

5. Conclusions

What drove the preference of Greek over Etruscan wine? Was it the desire for a less expensive product? Was it because Gauls liked the taste of Greek wine better? Did Greek merchants treat Gaulish farmers better than their Etruscan counterparts had? These are not questions that can be answered with an agent-based model, but would rather need to be examined through the archaeological record and through primary texts. However, the model presented here enables us to begin to ask these open questions, since we now know through systematic analysis that preference can drive artifact assemblages. Gauls preferred Greek amphorae, and likely the contents within them, over Etruscan amphorae, and it was through this demand that the artifact assemblage changed so rapidly and completely. If Etruscan amphorae signaled wealth or prestige, archaeologists should see them much later in the archaeological record. Instead they are discarded and recycled to make way for new Greek ceramics.

Debates about the causes of the complete replacement of Etruscan amphorae by Greek amphorae, as reported in Figure 3.1, are longstanding for this area. This research directly intervenes in these debates. The importance of this work is that the replacement event might be understood from internal, rather than external, processes. While further studies would need to take into account economic decisions—such as Greek amphorae being less costly to produce—this work begins these debates and allows for a thorough and systematic study of the distribution of wine types across the littoral. Further, this simple model shows that using a modeling approach can help shed light on complex processes. This model provides a useful tool to support the hypothesis that it is the demand for wine that drove these artifact patterns, not necessarily the availability of products (Villard 1960). Gaulish people were the creators of the economy of southern France, and their preferences drove what we see in the archaeological record.

This model is meant as a first step toward understanding the complexities of early colonist interactions in southern France, as well as a first step toward understanding how France became a viniculture powerhouse. The modern wine industry in France has roots that date back to the founding of the wine trade between Etruscans, Gauls and Greeks, and it is through the development of this complex economy that the wine industry exists today (McGovern et al 2013). Even though this model may be simple, it helps advance our understanding of local populations as drivers of the economy of a globalizing antique world.

Acknowledgments

I would like to thank Laure Nuninger, François Favory, Tim Kohler, and Rachel Opitz for guidance in developing this model. Further, I would like to thank Andrew Duff and Kathryn Harris, as well as two anonymous reviewers who helped to edit this work. This work also is indebted to each member of the TransMonDyn research group, who have commented on, guided, and listened to countless versions of this project. This work is also indebted to Michel Py and Michael Dietler, whose foundational work in understanding colonial interactions along this region influenced this model. Crabtree recognizes funding from the NSF Graduate Research Fellowship #DGE-080667 and the Chateaubriand Fellowship Program for helping fund this work. Crabtree created this model, wrote this paper, and did the analyses herself; any errors or mistakes are strictly her own.

Conflicts of Interest

The author declares no conflict of interest.

CHAPTER 4: AN EXAMINATION OF THE FORMATION OF POLITIES AMONG ANCESTRAL PUEBLOS

The second model completed for this dissertation examines the development of hierarchy within the Ancestral Pueblo southwest. In the 1980s a debate as to the hierarchical nature of the Ancestral Pueblo people began, with some finding the modern relatively egalitarian descendants of Ancestral Pueblos as evidence for a lack of social stratification in the past, and others finding the development of Chaco Canyon as antithetical to egalitarian social structure. Discussion of the hierarchical structure of Ancestral Pueblos has persisted; yet research into the high status of individuals at Chaco Canyon (e.g., Lekson 2015) seems at odds with other studies that have found little social stratification among the Ancestral Pueblo of Mesa Verde (e.g., Kohler and Higgins, 2016). Which of these interpretations is correct?

In the work presented here I, along with four coauthors, examine two new archaeological datasets for hierarchical organization. First, I examine the possible size of maximal groups that would use kivas and great kivas during Pueblo II and Pueblo III times in three regions—the Northern San Juan, the Middle San Juan, and the Chacoan core and periphery—for evidence of hierarchy. I subject these data to power-law analyses, since the processes that form power-laws strongly indicate an uneven distribution of wealth (e.g., Bettencourt 2007). I find that the Pueblo II kiva data display the strongest evidence for hierarchical organization, with less evidence for hierarchy during Pueblo III times. Then, I examine momentary household population data within the Northern San Juan region, focusing on the VEP II northern study area. Subjecting these data to the same suites of tests used in the kiva group-size dataset, I find that momentized household populations suggest a strong hierarchical organization during Pueblo II times, with a weakening hierarchical organization during Pueblo III times.

While these data may suggest that hierarchy was present, they do not hint at how hierarchy developed within the region. For this we created an agent-based model, "Polity," built on the Village Ecodynamics Project's agent-based model "Village." This model enables the examination of how households would choose to group together into territorial groups and how these territorial groups would come into conflict and form hierarchies between groups.

When subjected to power-law analyses, the simulated group-size data also shows a strong hierarchical distribution during Pueblo II times, with weakening hierarchy by the end of Pueblo III times. The only exogenous effects modeled in the simulation are those tied to the 700-year climatic regime of the region. This suggests that the seeds of hierarchy are intricately coupled with the productivity of the landscape.

The following chapter shows how conflict and taxation interrelate with group size to create complex hierarchies of groups within this region. This work suggests that not only is hierarchy possible for the Ancestral Pueblo southwest, but it is probable. Further, our simulation data echoes the findings in the empirical data, that hierarchy was strongest during Pueblo II times, and that it began to dissolve toward the end of Pueblo III, when Ancestral Puebloans invented new political and social organizations to confront the challenges of a rapidly deteriorating landscape.

How to Make a Polity (in the central Mesa Verde region)

Stefani A. Crabtree[1,2], R. Kyle Bocinsky[1,3], Paul L. Hooper[4,5], Susan C. Ryan[3], and Timothy A. Kohler[1,3,5,†]

1. Washington State University, Department of Anthropology, Pullman, WA
2. Université de Franche-Comté, Maison des Sciences de l'Homme et l'Environnement, Besançon, France
3. Crow Canyon Archaeological Center, Cortez, CO
4. Emory University, Department of Anthropology, Atlanta GA
5. The Santa Fe Institute, Santa Fe, NM

† . Corresponding Author: tako@wsu.edu

Abstract: The degree to which prehispanic societies in the northern upland Southwest were hierarchical or egalitarian is still debated and seems likely to have changed through time. This paper examines the plausibility of village-spanning polities in the northern Southwest by simulating the coevolution of hierarchy and warfare using extensions to the Village Ecodynamics Project's agent-based model. We additionally compile empirical data on the population size distribution of habitations and ritual spaces (kivas) and the social groups that used them in three large regions of the Pueblo Southwest, and analyze these through time. All lines of evidence refute an "autonomous village" model during the Pueblo II period (A.D. 890–1145); rather, they support the existence of village-spanning polities during the Pueblo II and probably into the Pueblo III period (A.D. 1145–1285) in some areas. One or more polities connecting the northern Southwest, with tribute flowing to an apex in Chaco Canyon, appears plausible during Pueblo II for the areas we examine. During Pueblo III, more local organizations likely held sway until depopulation in the late 13th century.

El extremo hasta en el que las sociedades prehispánicas en el Suroeste Americano eran jerárquicas o igualitarias aun es tema de debate, y probablemente cambiaron a través del tiempo. Este artículo examina la posibilidad de estados nacientes al nivel de múltiples villas en la región norte del Suroeste por medio de simulaciones de la co-evolución de la jerarquía y guerra en una extensión del modelo basado de agentes del proyecto Village Ecodynamic. Adicionalmente, recopilamos información empírica en tres regiones mayores del Suroeste, sobre la distribución de tamaños de la población en áreas sociales, de habitación, y espacios rituales (kivas). Estas líneas de evidencia refutan el modelo de "villas autónomas" durante el periodo Pueblo II (890–1145 d.C.). En vez, esta evidencia apoya la existencia de estados nacientes al nivel de múltiples villas durante el periodo de Pueblo II y probablemente Pueblo III en algunas áreas (1145–1285 d.C.). Uno más estados nacientes conectando el Suroeste norte, con tributos moviéndose al ápice en Chaco Canyon, parecen posibles durante el periodo de Pueblo II en esta área. Durante Pueblo III, organizaciones locales probablemente tomaron influencia hasta la despoblación al final del siglo XIII.

The causes of the growth and spread of hierarchical societies, so common in the post-Neolithic world, still deserve more exploration. It is perhaps curious that southwestern archaeology, which has made so many other contributions to finely resolved culture history and process, has on offer no general model explaining how such societies can emerge and be maintained. Indeed, for the last decade of the twentieth century and the first decade of the next, most southwestern archaeologists (with a few notable exceptions such as Feinman et al. 2000, Plog 1995, and Sebastian 1992) pursued other problems.

This likely reflects not just fashion in archaeology; the extent to which village-spanning political hierarchies and regional social stratification existed among Ancestral Pueblo societies remains controversial among Southwestern archaeologists three decades after a wrenching debate on this very subject (e.g., Cordell and Plog 1979; Lightfoot and Feinman 1982; Reid and Whittlesey 1990). That is, for some archaeologists there is little to no sociopolitical complexity to be explained. Characterization of ethnographically documented Pueblos as peaceful and egalitarian invited interpretations of their ancestors as adhering to similar norms. Indeed, examining household-level distributions of storage and living areas on the northern edge of the Pueblo world, one of us has recently argued that ritual in Pueblo I (PI) societies[1] had a leveling effect among households, limiting the accumulation of wealth differences to no more than expected in a typical horticultural society (Kohler and Higgins 2016). But to infer a history free of hierarchy from arguments for relatively egalitarian societies in contemporary and recent times, even bolstered by archaeologically derived inferences for leveling of wealth accumulation in some early Pueblo societies, is possibly too facile. What happened in between?

One does not have to maintain that states were ever present in the prehispanic Southwest to see the potential relevance of the claim that "nowhere in the world did the development of a state equipped with impersonal, pragmatic bureaucracy and coercive, disciplinary force happen overnight, leaping directly from a small autonomous village, the integration of which was based primarily on face-to-face contacts among its members" (Inomata and Coben 2006:11). We will argue that Chaco represented a complex hierarchical society—an example of a society in the gap identified by Inomata and Coben. We will first show why this is likely, and then we will demonstrate how it could have happened from non-hierarchical (indeed, probably anti-hierarchical) precedents.

The most well-known archaeological complex in the Pueblo Southwest, which began to form in Chaco Canyon during late PI times, displays clear aggrandizement and evident consolidation of power if we interpret great houses to be "palaces" of nobles and view the nearby, less labor-intensive contemporaneous habitations to be commoners' residences, as argued by Lekson (e.g., 2015:37–38). Chacoan influence spread over most of the Pueblo Southwest by the mid-to-late Pueblo II period (PII: 890–1145), as established beyond reasonable doubt by a number of shared features (including great houses) discussed in contributions to Lekson (ed., 2006).

The interpretation of these societies as hierarchical (or at least non-egalitarian) is strengthened by the two exceedingly rich burials from Room 33 in Pueblo Bonito, the largest and one of the oldest great houses in Chaco Canyon (Plog and Heitman 2010). The two males in Room 33 were interred in the ninth-century A.D. with the largest assemblage of ritual paraphernalia known from the Pueblo Southwest: intricately carved wooden sticks; wooden flutes with decorative designs; a shell trumpet; nearly 25,000 pieces of turquoise including beads, mosaic pieces, inlays, and carved ornaments; shell bracelets and beads; abundant ceramics including several unusual forms; a cylindrical basket covered in a mosaic of turquoise; several human skulls; and a formalized cache of arrows and wooden staffs in the adjacent Room 32 (Pepper 1909)—all or most interpreted as curated heirlooms and ritual sacra (Heitman 2015).

The next-largest set of great houses, in the Chaco-derived Aztec complex north of Chaco Canyon, also contained an unusually rich burial—an exceptionally tall male buried with a number of items (a coiled basketry shield, a wooden sword, a knife, and hafted axes or mauls) suggesting his nickname "the Warrior" (Morris 1924:193–195). The burials at Pueblo Bonito were likely emulated elsewhere on the Chacoan periphery, including the twelfth-century burial of "the Magician" in the Sinagua area at Ridge Ruin (Gruner 2015; McGregor 1943). Gruner (2015) argues that the ritual paraphernalia associated with the Magician burial signals a common material identity between the occupants of Ridge Ruin and Pueblo Bonito. The burials in Room 33 at Pueblo Bonito, the Magician, and the Warrior are strikingly unusual among prehispanic Pueblo burials, and imply heightened wealth and status of the interred individuals, perhaps in part derived from several ritual roles. Direct evidence from burial assemblages for similar hierarchy is generally lacking or is at least much more muted within the Pueblo world before PII and after Pueblo III (PIII: A.D. 1145–1285).

But how much weight should we place on hidden and rare features, such as these burials, in inferring social hierarchy that (were it fundamental) must have benefitted from widespread support and participation that should be visible in more mundane features? Here we offer a generalizable approach to examining hierarchy by describing transitions in site- and structure-size distributions through time for portions of the northern Southwest at three spatial scales—the simulation boundary in Figure 4.1, the greater VEPIIN boundary in Figure 4.1 which encompasses much of the central Mesa Verde region, and the greater Southwest which incorporates the Northern San Juan, the Middle San Juan, and the Chacoan core and periphery.

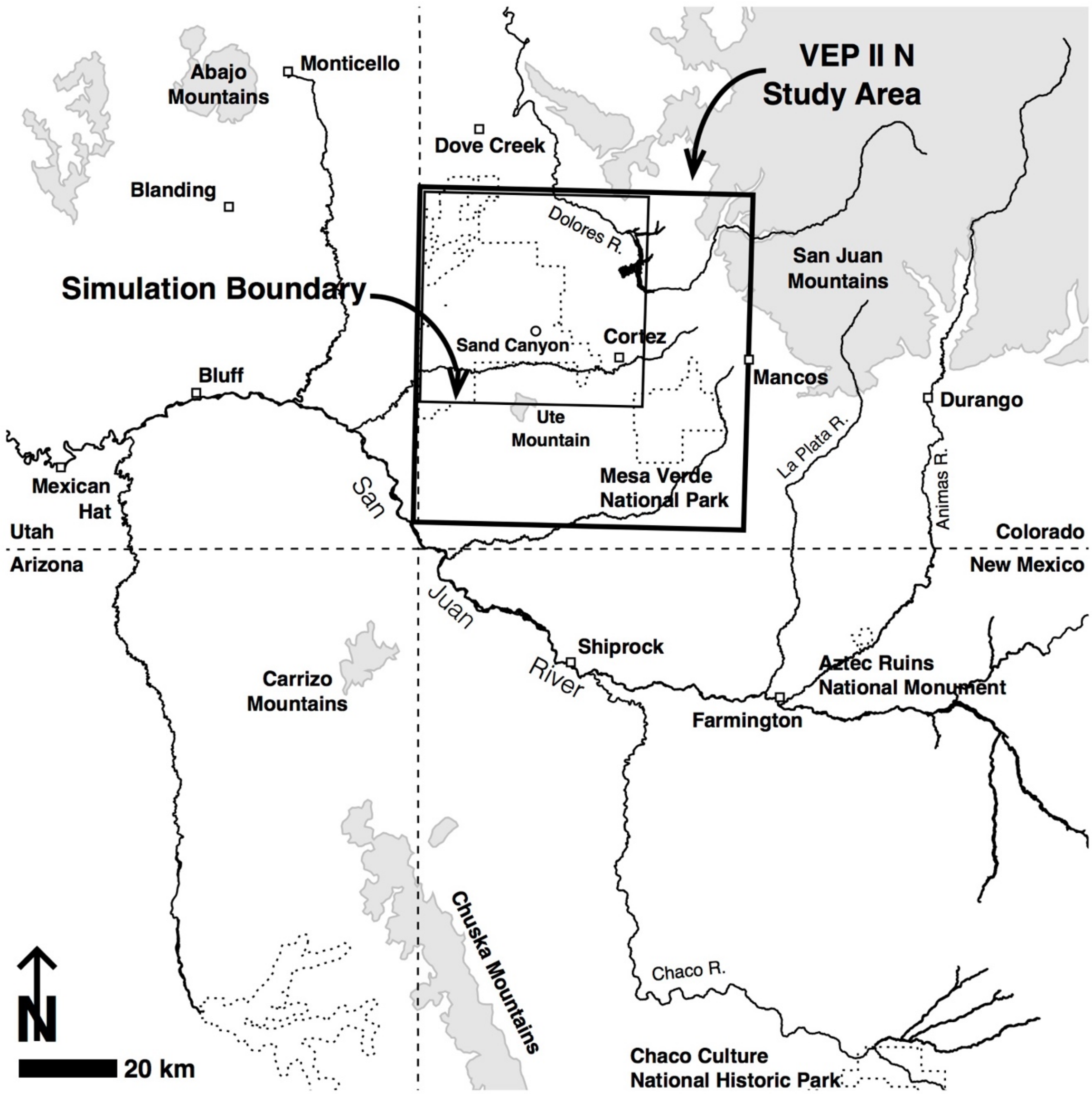


Figure 4.1. Location of the VEP I study area (shown by simulation boundary) within the VEPIIN area, which encompasses the most populous portion of the central Mesa Verde region.

Abundant, well-preserved archaeological traces in the Southwest enable us to examine final products of years of planning and group cooperation, as materialized in great kivas, for example. Such data form *patterns* to be explained, yet they are more or less silent on the *processes* creating those patterns. We must turn to models as descriptions of--and potential generative explanations for--those processes, and then return to the archaeological record to determine whether the models are capable of generating patterns more or less similar to those we encounter. We build on the Village Ecodynamics Project's (VEP) simulation "Village" to explore the consequences of hypotheses about the process of hierarchy formation. The processes on which we focus are the collaboration of households within groups, the growth of leadership within groups in tandem with the growth of groups, and the formation of groups-of-groups (polities) in the context of competition over arable land. We then compare the demographic patterns and the distribution of polity sizes generated by the simulation with the empirical evidence presented here on characteristics of size distributions for kivas and settlements. The thread connecting these disparate datasets will be an *inference* of generating process from the nature of the size distributions, and an *explicit definition* of (what we claim to be) the same process in the simulation, which generates size distributions similar to those identified for kivas and settlements.

In the following section we introduce useful concepts for characterizing the structure of size relationships among kivas and settlements. In the third section we examine site and kiva size distributions using these concepts. Then we introduce a model capable of generating similar size relationships among growing inter-village polities and explore its behavior using various parameterizations on virtual landscapes resembling a 1,817 km^2 portion of southwestern Colorado between 600 and 1280. Harmonies between the empirical record and the simulation results suggest that sociopolitical processes in large portions of the Pueblo world during the PII and portions of the PIII periods were substantially different from both earlier and later times, indicating the development, and eventual partial dissolution, of village-spanning political hierarchies.

Nestedness, Hierarchy, Log-normality and Power Laws

Whether or not they exhibit hierarchies in power or wealth, human societies typically exhibit a nested structure that may be termed "hierarchical" in the more limited sense that units at each scale are nested within units at more inclusive scales (Haas et al. 2015; Johnson 1982). For example, group size of ethnographic hunter-gatherer societies scales from individuals to families, bands, villages, and large aggregates (Hamilton et al. 2007). This scaling, or nesting, may enable efficient movement of information among all members of the group (Bernardini 1996; Kosse 2000; Lekson 1990) though several other possible functions for the larger scales (beyond those that are typically co-resident) have been proposed (Lehman et al. 2014; Kosse 1994; Lekson 1990). The concept of "Horton orders" describes the scaling constant relating the numbers of groups of similar sizes that participate in or belong to groups of the next larger size, which in turn nest within yet larger groups. In many cases the larger groups encompass 3 to 4 (Hamilton et al. 2007; Zhou et al. 2005) of the next-smaller-size groups, and if this ratio is constant as the scale increases, it is said to be self-similar. (The term "Horton order" commemorates Robert Horton's [1945] calculations of the average number of streams flowing into ever larger streams.)

Many archaeologists have suggested that during the PII and PIII periods one or more regional system(s) featuring at least three tiers of site sizes can be discerned in many portions of the Pueblo region, with the largest great house sites (community centers) at the top, followed by significantly smaller sites with more modest great houses, and the vernacular "Prudden unit" hamlets at the bottom. Powers et al. (1983:Table 41; see also Judge 1989:222) recognized three site-size tiers within just great house floor-area estimates, implying a four-tiered hierarchy overall if small villages and hamlets without a great house were part of the same system. Some (e.g., Lekson 2006:32–33; 1984:267) see this site-size hierarchy—with the great houses in Chaco Canyon at the top of the pyramid and sites outside the canyon as second or third tier—as evidence for sociopolitical hierarchy. Others (e.g., Johnson 1989) propose that the observed distribution of site-sizes can be explained by the concept of "sequential hierarchy," a relatively egalitarian organizational alternative to elites, forming in response to increasing group membership generating "scalar stress" and driving group fission.

Alberti (2014) recognizes that change from simple nesting of group sizes as a result of decision-making via a sequential hierarchy—in which no differential power may be implied—to a site-size hierarchy that implies power differentials will take multiple steps. In general, it is reasonable to presume that sequential hierarchies may constitute a "middle stage between fission and the emergence of non-consensual (i.e., hierarchical) decision-making bodies" in a growth process (Alberti 2014:3). Fissioning might be the immediate group response to scalar stress in contexts where that is possible (Lyman 2009) and such processes might not generate group integrative facilities and would also not imply hierarchies.

In more densely occupied landscapes, fission might not be possible, or easy, and we might expect ritual facilities to appear, providing locations for "sequences of redundant and invariant acts … [which] can ameliorate scalar stress by promoting an effective communication flow and by fostering in-group consensus and cohesion" (Alberti 2014:2; see also Adler and Wilshusen 1990). Coward and Dunbar (2014:388) suggest that more-or-less universal appearance of such structures is due to the fact that "elaborating the 'settings' for social interaction [with ritual facilities for example] simplifies social interactions and performance by off-loading the social information necessary for effective interactions from human memory into the material environment."

Such facilities are likely to become necessary as community sizes exceed ~150 members and are likely locations for religious practices that require investment of time, currency, or adherence to various forms of self-denial, making participation costly enough to deter fakers (Coward and Dunbar 2014:390). Performances are likely to include rhythmic dancing, chanting, and even laughter, triggering the release of endorphins, enhancing group solidarity and encouraging pro-social tendencies within the group (Coward and Dunbar 2014:392–393). By themselves, the presence of such facilities need not indicate significant power differentials, though if further growth eventually prompted the emergence of doctrinal religions, development of religious hierarchies might be expected. We will suggest that analysis of the size distributions of some of these facilities (kivas and great kivas) provides insight into the processes that generate them and that in turn are relevant to questions of differential social power.

We acknowledge that what we call kivas here likely had multiple functions, often quotidien but occasionally sacred. Our concern is for the capacity for social integration that these structures embodied at the scales of organization for which they were intended and their ability to reinforce social integration (and potentially hierarchy) through their use.

Turning to the question of site sizes, Duffy (2015) identified at least five processes other than regional political hierarchy capable of generating site size hierarchies in the archaeological record. Three of these result from time-averaging effects that are minimized by the relatively fine dating employed here (anchored by tree-ring dating, extended to ceramic depositional signatures). One of the other processes Duffy mentions, however—growth differentials due to differences in catchment productivity—must be considered before interpreting hierarchies in site-size histograms as possible evidence for regional functional specialization. Glowacki and Ortman (2012) examined potential maize productivity (derived as explained by Kohler 2012) for the 90-some community centers in the study area within which the simulation is set (see Figure 4.1). Community centers are the largest sites in their neighborhoods, usually contain civic-ceremonial architecture, and tend to be occupied longer than is typical for smaller habitations. Glowacki and Ortman showed that the peak population of centers is only weakly associated with the estimated mean maize productivity of their surrounding 2-km catchments ($r^2 = 0.07$; $p = 0.02$). As maize constitutes 70 percent or more of the local diet its productivity is highly relevant (Coltrain et al. 2006; Matson 2016). This suggests that variability in community center size was greatly influenced by factors other than catchment productivity, though catchment productivity is *not* irrelevant.

Following Duffy (2015), this suggests that the community-center size differentials we see in this area represent regional functional specialization, for example as the outcome of a political/economic structuring process. This also appears likely based on what we know about differential representation of structure types through time. Group-assembly features such as great kivas and plazas are present in most of the pre-980 community centers. In the 1000s, restricted-use features (especially great houses) become the most common civic-ceremonial architecture, replaced in turn after 1140 by controlled-access features such as towers and enclosing walls until regional abandonment in the mid-to-late 1200s (Glowacki and Ortman 2012:Table 14.2). By the mid-1100s great kivas become characteristic of only the largest centers, suggesting that they served as periodic group-assembly points for a number of surrounding smaller centers, defining a hierarchy that was simultaneously geographic, ritual, and size-based.

Two previous studies have characterized site-size hierarchies in this region. For the central Mesa Verde region (an area larger than—though encompassing—the areas for which we have settlement-size data and simulation results) Lipe (2002:217–220) studied habitation sites with an inferred momentary population of 50 or more. On the basis of a rank-size analysis he determined that from 1150–1225, sites exhibit a “well-integrated settlement system” in which the ranks plotted against the sizes approximate the expected diagonal (log-normal distribution) very closely. For the 1225–1290 period, however, the ranks plotted against the sizes deviate convexly upward from the diagonal, usually interpreted as indicating the presence of several competing systems.

For the same region examined in the simulations reported here, Kohler and Varien (2010) characterized the distributions of all sites with more than one household for 14 periods from 600 to 1280; their Figure 3.5 displays rank-size graphs for four of these periods. Generally, their results echoed those of Lipe (2002) where their periods overlapped, although they additionally recognized a slight tendency for the largest site (which after 1060 is Yellow Jacket Pueblo) to be larger than expected (until at least 1140) by the rank-size metric. They suggested that this tendency towards primacy for Yellow Jacket Pueblo measured "the degree to which it drew benefits—unknown in nature—from other settlements through processes that remain to be defined" (2010:54).

Here we will apply recent advances in characterizing scaling relationships to sharpen these arguments, using empirical estimates of kiva sizes (and the groups they could accommodate), momentized site populations, and territory sizes for groups of sites generated by the simulation. To shed light on the processes that generate such distributions, we focus on whether these correspond more closely to a log-normal or to a power-law distribution. Although these distributions look somewhat similar (both have long tails to the right and so exhibit positive skew in which, for example, small sites are common but large sites rare) they differ in their generating processes in ways that relate to the equality of their constituents.

If the size of some variate (e.g., settlement population) is graphed against its frequency, and the distribution is normal (Gaussian) when the logarithm of the size is used, the distribution is said to be log-normal (Aitchison and Brown 1957:1). Log-normal distributions are classically produced by something which can be called the law of proportionate effect (Aitchison and Brown 1957:1) or the multiplicative process (Mitzenmacher 2004:235). If settlements grow (or shrink) in response to a number of unrelated processes, each of which is proportionate in its effect to the size of the settlement in the previous time step, the expected result is a log-normal distribution of settlement sizes.

If settlement sizes (or kiva sizes) conform to a log-normal distribution, we will argue that this implies the outcome of a number of unrelated processes, but importantly *not* including a process in which largeness itself was disproportionately rewarded. Power-law distributions, on the other hand, are classically generated by preferential attachment. An example would be a case in which the largest existing settlement is also the preferred target for migration. (Mitzenmacher [2004:233–235] also mentions optimization as a possible process leading to power-law distributions, though its efficacy has been debated.) Some variate, x, obeys a power-law distribution if it is drawn from the probability distribution $p(x) \propto x^{-\alpha}$, where α is a scaling exponent typically taking on a value between 2 and 3. We have known since Albert et al. (1999) that the in-degrees and out-degrees of nodes in the worldwide web are commonly power-law distributed and the reasons that more popular nodes will be preferential targets for new links seem obvious in this case.

Power-law-like distributions frequently indicate the outcome of processes such as consolidation of power and growth of hierarchy (Grove 2011). Modern city population sizes follow a power-law distribution (e.g., Auerbach 1913; Bettencourt 2013; Bettencourt et al. 2007) because large aggregates create increasing returns in wealth and innovation, in turn attracting to themselves a growing number of people. In our data, we will argue that settlement-size distributions matching power laws suggest that the largest settlements were benefitting the most from the ritual or political system. To strengthen this inference we will present model results in which larger groups come to have a power advantage over smaller groups as regional population size and density increase, and demonstrate that this produces power-law-distributed territory sizes. Beyond the factors considered in the simulation, larger settlements would likely have served as engines of innovation and attracted more residents (Bettencourt 2007), more wealth (Brown et al. 2012), more ritual (Glowacki and Ortman 2012) and more feasting (Mills 2007)[2]. These benefits will in the event be balanced against the social and economic costs of being large, including alleviating size-induced social frictions, as well as traveling greater distances to fields and slowly renewable resources such as deer and firewood.

With these ideas in mind we begin by examining data on kiva sizes for the large portion of the Pueblo Southwest studied by Ryan (2013:Figure 2.1). We then turn to estimated population sizes for habitations (including community centers) in the VEPIIN area (Figure 4.1). Using these two datasets may allow us to profit from convergence of semi-independent lines of evidence. In both cases we attempt to determine whether their size distributions through time correspond to a power law, which might suggest the development of supra-village polities, or exhibit log-normality, which suggests a variety of non-hierarchical generating processes. After introducing the simulation model, we will also compare the distributions of territory size generated by the simulation to these two theoretical distributions.

Scaling Relationships in Archaeological Data

Kiva Sizes

For the last three decades archaeologists in the central Mesa Verde region have identified small kivas (with diameters less than 10 m) as serving a domestic function in addition to focusing some ritual activities at the level of the household, extended household, or lineage group. Larger structures such as great kivas (10 m or larger) focused non-domestic ritual activities for one or more communities (Adler and Wilshusen 1990). If we grant that kiva sizes are related to the sizes (and types) of the groups they served, and if settlements have fairly discrete hierarchical size categories (e.g., hamlets and villages), we might also expect kiva dimensions to exhibit fairly discrete size classes. Further, if either of these size distributions appears more likely to have been drawn from a power law than a log-normal distribution, that will be taken as evidence for some type of reward for largeness—such as the processes we define for the simulation—in and of itself.

Susan Ryan (2013) compiled data on 407 fully excavated kivas of all sizes during PII and PIII periods within three large subregions of the prehispanic Pueblo Southwest: the Northern San Juan (NSJ), centering on though larger than the central Mesa Verde region; the Middle San Juan (MSJ), centered on the Aztec area; and the Chaco Core and Periphery (CCP), centered on Chaco Canyon. Of those 407 structures, we used the 248 having bench widths, and added 224 kivas to her dataset, mostly in the NSJ, whose diameters could be estimated accurately, even if they were not fully excavated. Diameters in Ryan's data were computed from bench-face to bench-face (Ryan 2013:133, 136); diameters for additional pitstructures we added here were computed by measuring the interior of kiva-circles on maps. Our total sample of 472 structures represents an unknown proportion of the total population of PII-PIII-period preserved kivas in these regions. It is highly probable that our sample is overweighted towards larger size classes since they are more noticeable and more likely to have been investigated.

Of greater interest than the diameters of kivas, however, are the group sizes that they could accommodate. One approach to estimating these is simply to assume that each person needs a square meter of space, so that a 7-m-diameter kiva (with a floor area of 38 m^2) could accommodate a group of 38 (Van Dyke 2007a:119). Alternatively, one might partition the space into spectator and performance space.

Of course, "performance space" means different things for great kivas and household kivas, and here we use the term broadly to incorporate both spectacles and performances, as defined by Inomata and Coben (2006). *Spectacles* are "gatherings linked around theatrical performance of a certain scale in clear spatial and temporal frames, in which participants witness and sense the presence of others and share a certain experience" (Inomata and Coben 2006:16).

This assumes an audience, an emotional response, includes props, and incorporates a great deal of symbolic material. Events performed in great kivas would be spectacles typically witnessed by a group of people and incorporating many props such as foot drums and elaborate costumes laden with symbolic associations. Spectacles also incorporated participants outside the confines of the kiva walls through sound, adding to their scope.

Performance, on the other hand, includes "informal daily activities as forms of human interactions and self-presentations" (Inomata and Coben 2006:14). A performance, then, is any activity that can affect the life of the performer as well as a potential observer (Inomata and Coben 2006; Goffman 1959). Grinding maize, weaving a blanket, and teaching a child all fall within its scope. Such "performances" could have incorporated other people performing complementary tasks related to the activity at hand (e.g., preparing the kernels for grinding). We assume that each spectator (or maize-grinding helper) needs one linear meter around the circumference, and each "performer" needs 4 m^2 (a generous figure allowing for presence of floor features).

A kiva with a diameter of 7 m has a circumference of ~22 m and an area of ~38 m^2, allowing for 22 spectators and 38/4 = ~9 performers, or a total group size of 31. For pitstructures more than 4 m in diameter, this method yields lower group-size estimates than assuming 1 m^2/person. Even though we acknowledge that the activities in small and great kivas were typically different, we use the same formula to estimate the probable group size in both.

Using this approach we translate diameters into expected group sizes for kivas in the PII and PIII periods (Figure 4.2). The most dramatic feature in this figure is the loss of most large kivas (groups) in the two southern areas in the PIII period, with the exception of the Salmon Ruins great kiva (dated to PII–PIII by Windes and Bacha 2008:130) and the Chacra Mesa great kiva (dated to PII–PIII by Van Dyke 2007b:123). Multiple modes can be seen in most of these histograms.[3] In both the NSJ and MSJ during the PII period, modes occur around 15 and 25 participants, with possible larger modes in the 60–70 and the 80–90 range. Pueblo II CCP sites also exhibit modes around 15, 25, and 90, but unlike those to the north there is apparently an additional mode around 45 participants (most of these appear to be what Windes [2015] calls court kivas), and the unique great kiva, Casa Rinconada (Vivian and Reiter 1965:9–26) which, according to our (possibly conservative) rules, would have accommodated some 130 participants.

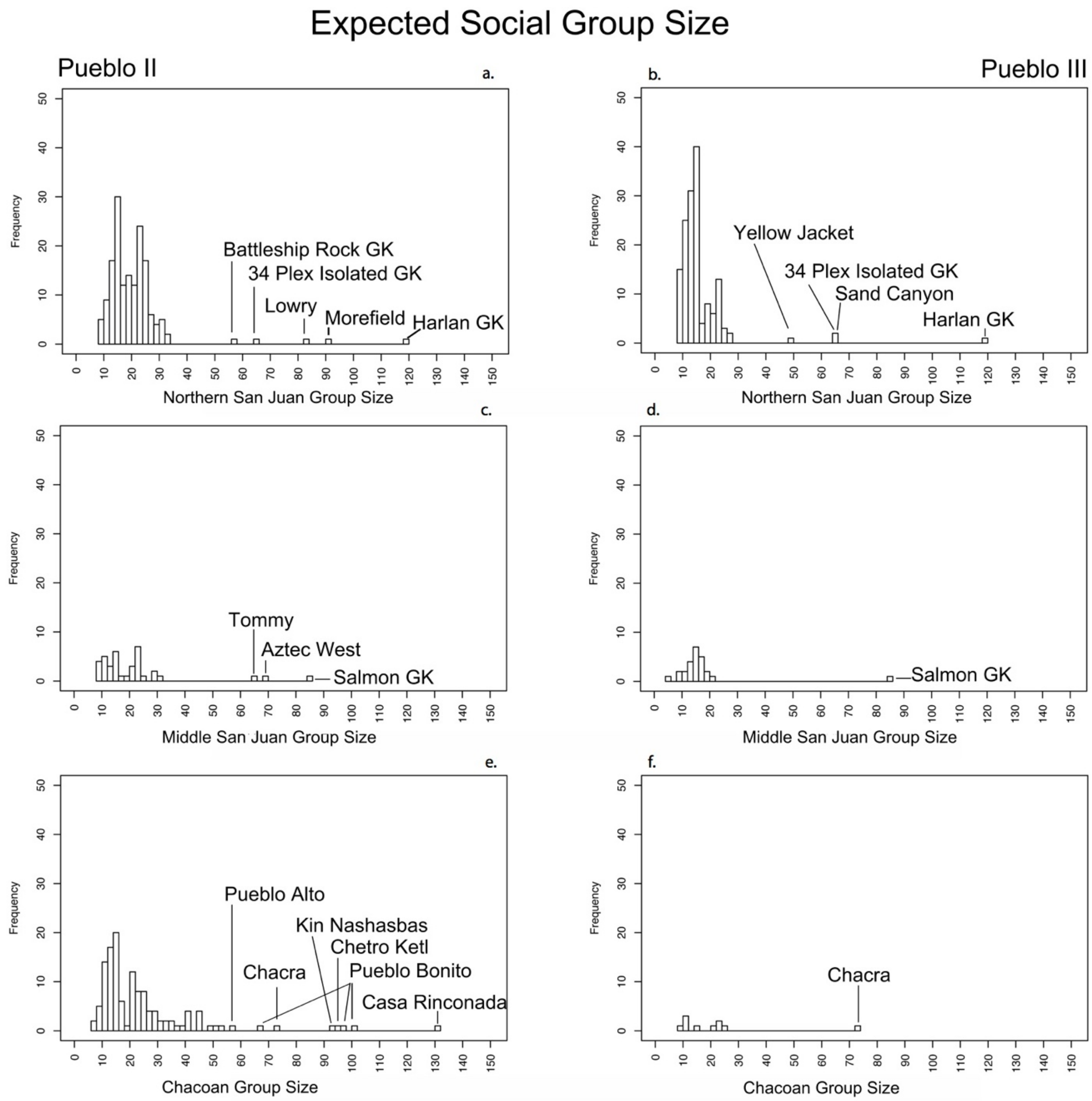


Figure 4.2. Expected social group sizes represented by kiva floor areas, calculated from kiva diameters assuming circular shape; PII, left column; PIII, right column. NSJ data are in the top row, MSJ data in the second row, and the CCP in the third row. Axes are standardized.

During Pueblo III the NSJ and CCP both retain modes around 10–15 and 25 participants, though the MSJ seems to retain only the smallest size class. In the NSJ there continues to be a possible mode in the 48–65 participant range, whereas the long-lived Harlan Great Kiva (Coffey 2014) in the Goodman Point community fills a Casa Rinconada-like role as the largest integrative structure in the region. Yet there seem to be fewer kivas overall, and fewer kivas in the middle-range of sizes, during the PIII period, although we know that open-air plazas, or common areas, as well as biwall and triwall structures increased in frequency (Glowacki 2015:69). Such spaces may have reduced the need to invest in costly and complicated kivas, and perhaps substituted in particular for kivas serving ~40–50 people. However, the functions of the multiwalled structures are uncertain, and plazas presumably served a variety of purposes. For these reasons we focus on kivas.

For these we can suggest a scaling parameter on the order of 1.7 to 2 (15 people *x* 1.67 = 25 people; 25 people *x* 1.8 = 45 people; 45 people x 2 = 90), suggesting that as ritual moved beyond the household, each larger structure might accommodate 1 or 2 of the people participating in the rituals in the next-smaller-size kiva. (This argument does not abandon the point of view that all non-great kivas had residential functions; it merely recognizes that such kivas also likely had ceremonial functions.) If we assume strict nestedness we can express the same result slightly differently. Kivas in the 25-participant size range should be aggregating their participants from about (25/1.67=) 15 of the 15-participant-size kivas; each kiva in the 45-participant size range should be drawing participants on average from about (45/1.8=) 25 of the 25-participant-size structures; and great kivas in the 90-participant size range should be drawing on about (90/2=) 45 kivas in the 45-participant size range. By this logic a "standard" great kiva accommodating about 90 people could serve representatives of (25 x 45=) 1125 of the social units represented by the smallest kivas—an interestingly high number which either suggests that strict nestedness did not apply, or that such great kivas could easily accommodate participants from two very large communities of >500 households each.

The relationship between the 90-participant great kivas and the 130 we estimate for Casa Rinconada has a somewhat lower scaling parameter (90 x 1.44 = 130) but if we nevertheless use the same logic it may have been drawing its 130 participants at the rate of 1 or 2 representatives each from about (130/1.44=) 90 of the 90-participant size great kivas. This might be plausible; the Chaco Research Archive (http://www.chacoarchive.org/cra/outlier-database/) lists 106 outliers with great kivas, not all of which may have been in use at once.

Although these numbers might seem to suggest an implausibly high number of households represented in increasingly large structures, Windes (2015) does argue that court kivas at Chaco were in many cases used by non-residents, and if the distance traveled to Chaco Canyon was great it is reasonable to expect that only one or two representatives of kivas in the 25-participant class might have made the journey. Van Dyke (2007:119) likewise suggests that great kivas accommodated only a "small fraction of the resident or visiting population," intentionally (one presumes) restricting access to that segment.

Chaco researchers are increasingly embracing regional analyses that imply a broad spatial scope for Chacoan social integration, if not explicitly arguing for a Chacoan polity. Van Dyke and colleagues (2016) demonstrate that shrines, stone circles, and herraduras enhanced visibility between great houses, and created a network of visual dominance over the landscape that seems to peak after AD 1000. Chacoan road systems betray regional-scale planning (if not functional economic integration; Kantner and Hobgood 2003), and roads and directional alignments between outlier great houses in the middle San Juan suggest subregional coordination for the observation of celestial events (Coffey 2016:14). It remains to be seen whether these systems evidence coordination and unity at the scale of the Chaco world, or merely a shared subregional identity that is undoubtedly influenced—but not controlled—by Chaco (Kantner 2003:218). Here, we argue that a regional system with Chaco at its core need not have its origins in a unified system, but instead can emerge from hierarchical power relationships that form at a local scale. As we shall see, kiva size distributions across the Pueblo Southwest reify and likely served to reinforce hierarchy at multiple scales of Pueblo society.

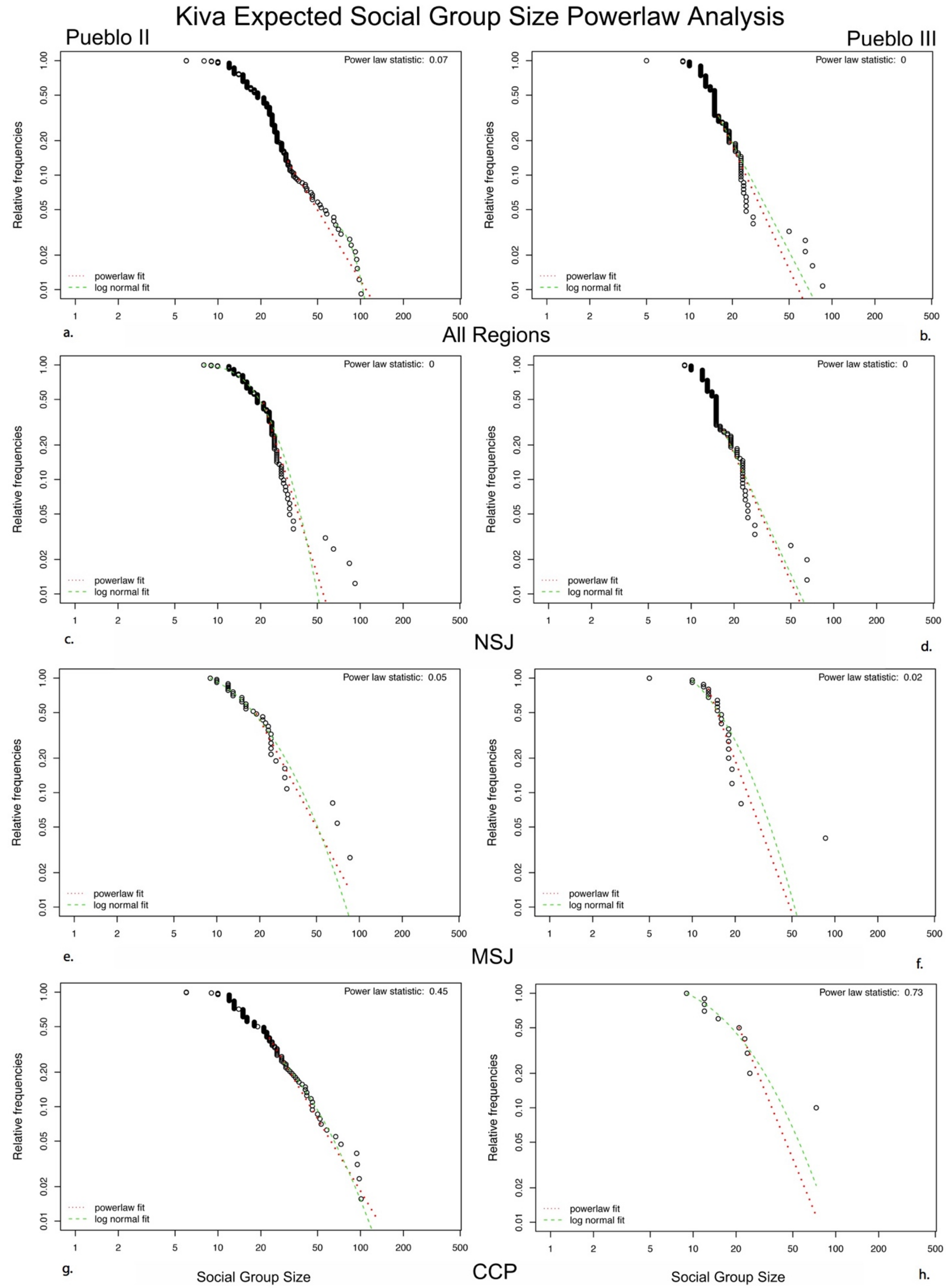
Analysis of Kiva Size Distributions

Now we examine these kiva data from the perspective of whether (and when) their size distributions fit those expected by a power law, using the log-linear distribution as an explicit comparison given the ease with which these two distributions can be confused. Many studies (e.g., Brown et al. 2012) identify the fingerprints of power laws based solely on visual inspection of distributions. Here we use the poweRlaw package (Gillespie 2015) which implements procedures suggested by Clauset et al. (2009) with results displayed in Figure 4.3. Since log-normal and power-law distributions differ primarily in their extreme right tails, Gillespie (2015) employs a Kolmogorov-Smirnov test to locate the minimum value in an empirical distribution at which a power law ought to apply, setting that as the x_{min} value for the test. We imposed the same x_{min} value on the log-normal distribution to facilitate comparison of the two.

Table 4.1 summarizes the results of this examination. The **alpha parameter** reports the slope of the best-fit power-law line; note for example in Figure 4.3 that the power-law-fit line slopes down more rapidly for NSJ PIII (alpha=2.9, Figure 4.3.d) than it does for CCP PII (alpha=1.8, Figure 4.3.g). Then we tabulate the results of several complementary tests that do not always deliver precisely the same conclusions. The **power-law probability** reports the probability that the empirical data could have been generated by a power law; the closer that statistic is to 1, the more likely that is. We consider values below 0.1 as rejecting the hypothesis that the distribution was generated by a power law (Clauset et al. 2009:16). The **test statistic** indicates how closely the empirical data match the log normal. Negative values indicate log-normal distributions, and the higher the absolute value, the more confident the interpretation. However, it is possible to have a test statistic that indicates a log-normal distribution in addition to a power-law probability that indicates a power-law, so we employ the **compare distributions** test to compare the fit of the distribution to a power-law and to the log-normal distribution. Values below 0.4 indicate a better fit to the log-normal; those above 0.6 favor a power-law; intermediate values are ambiguous.

Table 4.1. Summary of conformity of kiva-size distributions to power-law expectations. "Power-law probabilities" between 0.1 and 1 indicate inability to reject the hypothesis that the data could have been generated by a power law. "Compare distributions" values of 0.6 to 1 indicate a power-law; values from 0 to 0.4 indicate a log-normal distribution; intermediate values are ambiguous. Positive values for the "Test statistic" indicate power-law distributions; negative values indicate log-normal distributions.

Area and Period	Alpha	Power-law probability	Compare distributions	Test statistic
All PII	1.828	0.07	0.541	0.104
All PIII	1.881	0	0.669	0.440
NSJ PII	2.115	0	0.671	0.443
NSJ PIII	2.868	0	0.561	0.153
CCP PII	1.780	0.45	0.604	0.265
CCP PIII	2.378	0.73	0.566	0.166
MSJ PII	2.325	0.05	0.577	0.193
MSJ PIII	1.885	0.02	0.651	0.699



Kiva Expected Social Group Size Powerlaw Analysis
Pueblo II
Pueblo III
All Regions
NSJ
MSJ
CCP
Power law statistic: 0.07
Power law statistic: 0
Power law statistic: 0
Power law statistic: 0
Power law statistic: 0.05
Power law statistic: 0.02
Power law statistic: 0.45
Power law statistic: 0.73
powerlaw fit
log normal fit
Relative frequencies
Social Group Size
a.
b.
c.
d.
e.
f.
g.
h.

Figure 4.3. Power-law analysis of the expected social group sizes represented by kivas of various sizes, by period and region. Power-law probability values from Table 4.1 are reported in the upper right-hand corner of each panel.

Discussions with the developer of the procedure implemented in the poweRlaw package lead us to suggest that over-sampling of the larger kivas, in the NSJ in particular, is likely responsible for the somewhat contradictory results in Table 4.1, where "power-law probability" (when it rejects a power law) is often at odds with the "compare distribution" and "test statistic" indicating power laws. Clauset (personal communication 6/10/2016) suggests our results may indicate that the NSJ and Pll–PIII kiva data represent weak power laws (see Supplemental Text: Detecting Outliers in Kiva Size Distributions). Grove's analysis of ritual centers in Ireland (2010:Figure 5) showed that the largest stone circles in his sample also tended to weaken what appeared from the body of the distribution to be a power-law distribution.

With that in mind, the results from Table 4.1 generally support the inference that kiva sizes in Chaco Canyon and its periphery in PII and probably PIII times were generated by a power-law-like process. Elsewhere, this is slightly less clear, although in all three regions and in both periods power-law distributions fit the kiva data better than log-normal distributions do.

Analysis of Settlement Population Distributions

We now turn to the results of the same analysis based on estimates for the number of households in habitation sites by period, as compiled by Schwindt et al. (2016) for the subportion of the NSJ studied by VEPII, using only those sites assigned one or more households for that period. The site-size estimates used here were generated by steps 1–4 in Schwindt et al. (2016:78–80) which were then momentized by multiplying by the mean occupation span in each period from Varien et al. (2007:Table 3) divided by the length of each period. The histograms of site size (Supplemental Figures 4.1 and 4.2) show the expected pattern of many small sites and decreasing numbers of sites of larger sizes through all periods. Populations of the largest sites, however, tend to increase through time. Discrete modes are less visible in the settlement-size distributions than for the kivas; although the case for the presence of modes is visually stronger in the later periods (Supplemental Figure 2) we do not pursue their identification here.

In general, the site-size distributions are more clearly power-law-distributed than are the kiva sizes (Supplemental Figures 4.3 and 4.4; Table 4.2). Exceptions are the periods 1020–1060, 1060–1100, 1180–1225, and 1225–1260, all of which have one or two ambiguous indicators, although the "test statistic" in each case points to a power law. Rather surprisingly, the two earliest periods appear to correspond to a power law, though the results may be spurious since nearly their entire distribution after momentizing is composed of many one-household settlements.

Table 4.2. Summary of degree of conformity of VEPIIN settlement-size distributions to power-law expectations. "Power-law probabilities" between 0.1 and 1 indicate inability to reject the hypothesis that the data could have been generated by a power law. "Compare distributions" values of 0.6 to 1 indicate a power-law; values from 0 to 0.4 indicate a log-normal distribution; intermediate values are ambiguous. Positive values for the "Test statistic" indicates power-law distributions; negative values indicate log-normal distributions.

Years A.D.	alpha	Power-law probability	Compare distributions	Test statistic
600-725	5.57	0.3	0.991	2.385
725-800	2.23	0.3	0.672	0.445
800-840	3.21	0.22	0.672	0.445
840-880	3.14	0.55	0.623	0.331
880-920	3.59	0.43	0.835	0.975
920-980	3.11	0.46	0.591	0.230
980-1020	4.49	0.46	0.942	1.575
1020-1060	2.80	0.03	0.568	0.171
1060-1100	2.80	0.08	0.568	0.171
1100-1140	2.15	0.24	0.753	0.682
1140-1180	2.19	0.8	0.620	0.305
1180-1225	1.98	0	0.829	0.949

1225-1260	1.91	0.25	0.5751	0.189
1260-1280	1.88	0.3	0.643	0.366

Summary of Empirical Results

Overall, the case for processes such as preferential attachment (expected for power-law fits) is clear for PII and probable for PIII kiva-size distributions, particularly in the CCP. With a few possible exceptions the site-size distributions also conform to power-law expectations.

Of course, these outcomes only hint at an explanation for the development of this structure. Can a process of preferential attachment, or something like it, that withstands the test of plausibility for the societies represented here be built into a model that generates power-law structures for size distributions? For example, do the largest settlements (or groups of settlements) grow ever larger by drawing in (or compelling the participation of) more people for ritual, exchange, and other social functions? We now describe a model providing a candidate explanation for the empirical results reviewed so far.

The Model

The Village simulation is built on a foundation of trees. Ring-width analysis generates temporal series of annually resolved estimates of temperature and precipitation from AD 600–1300 that in turn generate spatialized estimates of potential maize productivity and the productivity of the various plants that provide food for deer, rabbits, and hares, and wood for cooking and heating. The agents in this model represent Pueblo households who farm maize, hunt deer and leporids, raise turkeys, fetch water and fuel, trade resources, and react to local variability in environmental productivity (also affected by local densities of other households) by relocating their settlements to more productive land, or by intensifying (adding more farm plots, raising more turkey in lieu of hunting). On top of this base simulation, described extensively in Kohler and Varien (2012), we add a number of changes allowing the agents to live in territorial groups of varying political organization and form polities.[4]

The model we propose makes three important but well-founded assumptions. First, as warranted earlier, we assume the centrality of maize in the Pueblo diet. The best lands to produce maize were worth competing over due to the dominance of maize in the diet and the high spatial variability in potential production. Second, we assume a strong trend of population growth during the periods considered here, which is clearly demonstrated for the Southwest as a whole (Kohler and Reese 2014) and for the VEPIIN area (Figure 4.1; Schwindt et al. 2016). Third, we build into the model the possibility of mortal conflict between groups, recognizing that these societies were subject to enough sporadic violence to rank them "among the most violent societies studied by anthropologists or archaeologists" (Kohler et al. 2014:458).

The model therefore features growing groups that may come into conflict over limited expanses of superior arable land. By virtue of their size, some of these groups are able to incorporate others, by force or threat, forming multi-settlement "polities" we call complex groups that can grow or shrink according to the climate-mediated production of the lands they encompass and the competition they encounter. These processes typically result in a chain of subordinate groups (or often a more tree-like structure) linked to a dominant group by flows of tribute in maize, mutual protection in defense, and coordinated action in offense. We demonstrate that this model results in territory sizes for these polities that are power-law distributed—unsurprising given that they are generated by a big-get-bigger dynamic—and we infer that flows of tribute and coordinated action could help generate the sorts of power-law-distributed settlement sizes (and therefore kiva sizes) we documented above for the archaeological record.

Space limits necessitate deferring most model details to the Supplemental Materials. (See sections therein on the public goods game; parameter selection, group formation and territoriality; conflict, merging, and tribute; revolt in complex groups; and fission in simple groups; also Kohler et al. in review.[5]) To the base "Village" model the model reported here adds a territorial, kin-based group structure in which households (agents) live in simple groups which annually play a within-group public goods game, deciding to elect a leader (the more costly alternative when groups are small) or perform mutual monitoring against defection (the more costly alternative when groups are large). Simple groups can therefore be either non-hierarchical or hierarchical. If a simple group reaches a population size parameterized in the simulation (either 50 or 100 households) it fissions (all parameters varied in the runs reported here are in Table 4.3)[6]. When group territories begin to encroach on each other, groups may merge or fight, in either case linking them into complex groups with a hierarchical organization. Subordinate groups in complex groups pay tribute to the ultimate dominant group, passing through any intermediate groups in the chain (Steponaitis 1981). Finally, simple groups (along with their subordinates, if any) may choose to revolt from their dominant group to form a simple group (by themselves) or a complex group (with their existing subordinates). Thus, the model unites the two relational mechanisms identified by Dubreuil (2010:140) as "intimately linked to the evolution of hierarchies"—emergence of corporate groups (our simple groups) and social division of sanction (the leaders who may appear in simple groups).

Table 4.3. Parameters varied in the runs of the simulation reported here. This created 36 unique runs, each replicated 15 times; replicates are reported in Supplemental Table 4. Max simple group size is the number of households beyond which the group will fission. S is the percent of fighters the smaller group will accept as casualties; e.g., a fight between a group with 100 warriors and a group with 200, and an s value of 0.02, will result in up to 2 fighters dieing. β is the tax on the net return to the public goods game, while μ is the tax on beta.

Max Simple Group Size (households)	*S* (acceptable proportion of fatalities among all combatants in the smaller group during warfare)	B (proportion of net benefit to public goods game paid as tribute to direct dominant group)	μ (portion of β passed to next dominant group by an intermediate group)

50	0.02	0.1	0.1
100	0.05	0.5	0.5
--	--	0.9	0.9

Our current model is generically similar to some earlier models (e.g., Cederman 2002; Cegielski and Rogers 2016; Griffin and Stanish 2007; Turchin and Gavrilets 2009) that feature competition, warfare, tribute, or polity emergence, disappearance, secession, and unification, and we gratefully acknowledge their inspiration. In general we endogenize more aspects of our model (e.g., production, population growth, and many household-level ecosystem interactions) than do others of which we are aware. To the extent that initial steps towards variability among households or groups of households in wealth and power (as studied by Wilkinson et al. 2007 for example) and successful maintenance of existing polities depend on control of the best patches for maize production, these differences are important. In our case, we suggest that the modest correlation of community center size with local maize productivity suggests that the processes of polity growth are initiated, and then best maintained, by sites enjoying access to superior maize production.

Simulation Results

Each of the 36 unique parameter combinations (Supplemental Table 4) was run 15 times, creating 540 total runs. Figure 4.4 reports the population trajectories of agents in each of these runs and for each of the parameter combinations. Runs with low fatalities to warfare (*s*), low taxation (β), and low pass-through tribute (μ) (that is, high amounts of the tax from subordinate groups retained within each group as tribute moves up the chain) generate the highest populations, which are most similar to those in the empirical record (Figure 4.4, gray bars). We think that the main sources for the differences between the simulated populations and the empirical population estimates are the lack of immigration and emigration in the model, and the fact that we do not model low-frequency climate change, which influenced productivity in our region to an unknown extent; these issues are discussed at length in Kohler and Varien (2012). The runs with the highest populations are: run 1 (blue line), run 2 (red line), and run 3 (blue-grey line). The higher *s*-value and higher taxation values generate the lowest populations (e.g., run 18 with $s = 0.05$, β and $\mu = 0.9$). Different thresholds for maximum simple group size do not markedly affect total population size; both the smallest and largest total populations were produced when group-size threshold for fission was set to 50.

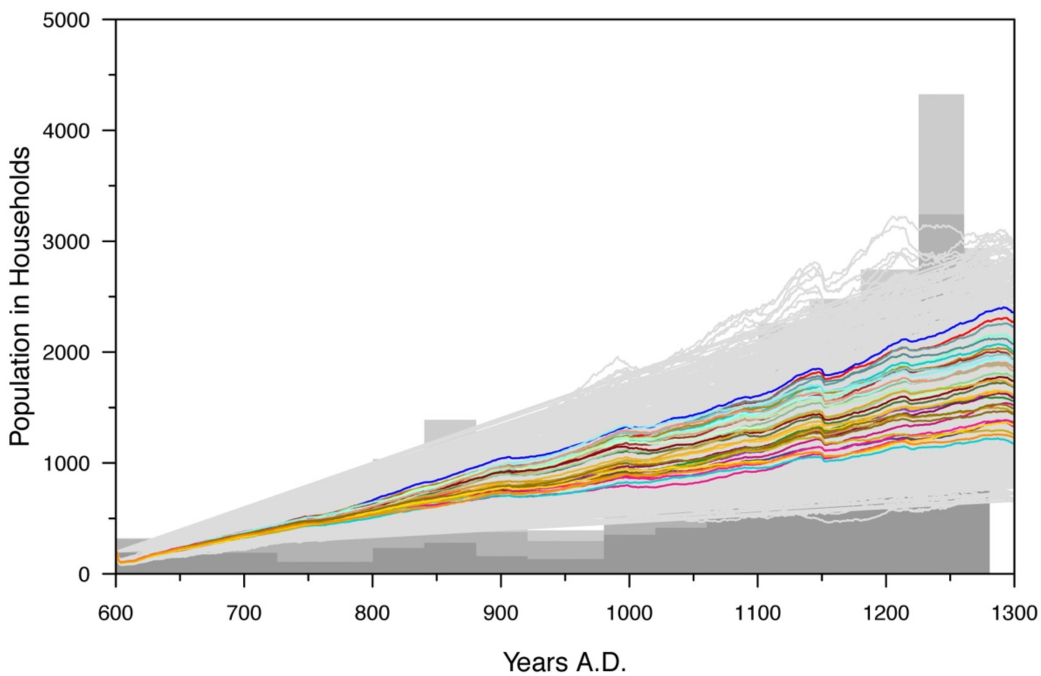


Figure 4.4. Central tendencies for simulated human population through time for each of 36 parameter combinations (in color), with each of the 540 unique runs plotted in grey over blocky histograms representing the empirical population estimates for the simulation area (from Varien et al. 2007). Schwindt et al. (2016) created newer population estimates, but for a larger region, so the older population estimates are retained here.

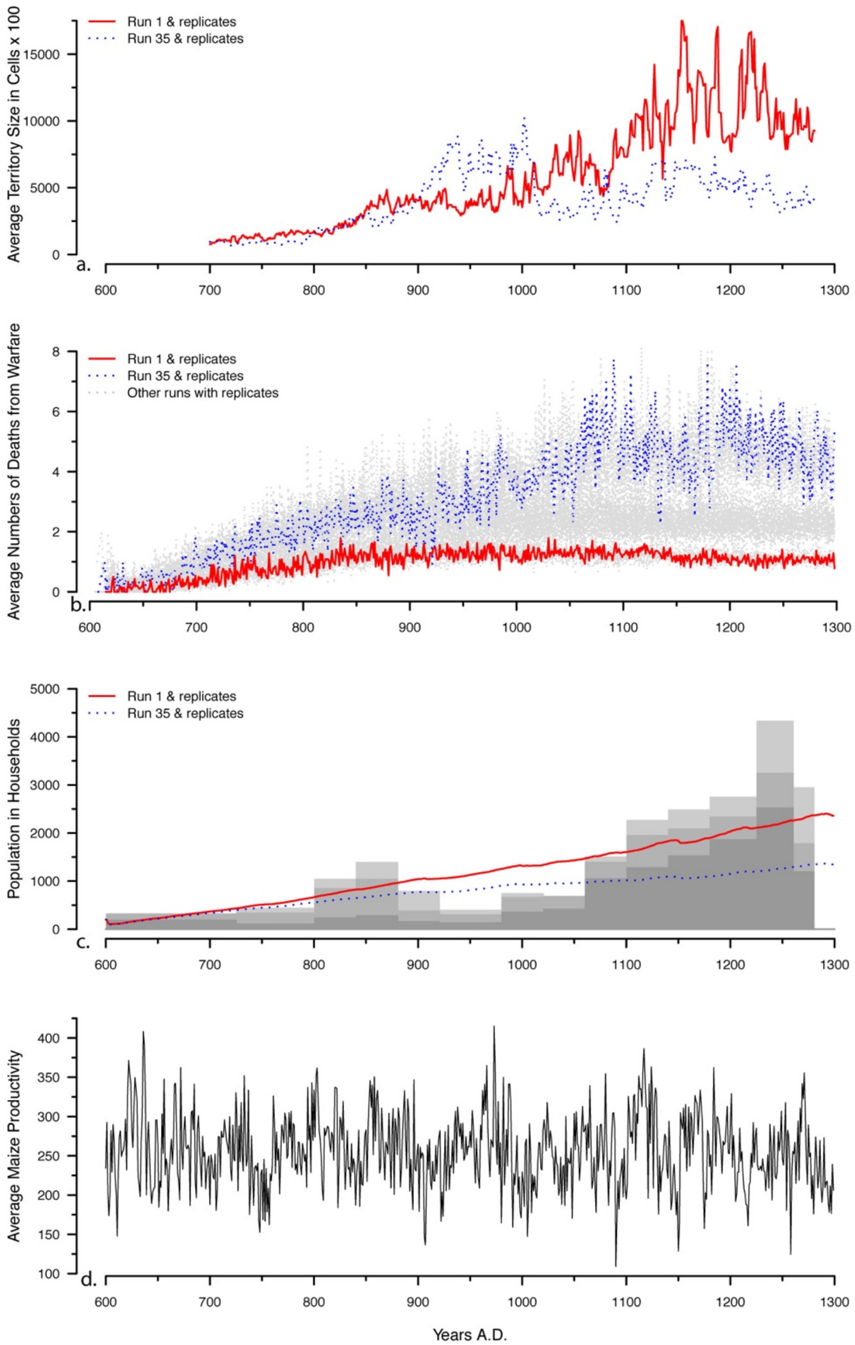


Figure 4.5. Panel 4.5.a: Average territory sizes through time for the largest groups of which each simple group is a member, for Run 1 and replicates, and Run 35 and replicates. 4.5.b: annual deaths from warfare. Grey lines indicate means for all runs with replicates; Run 1 and replicates and Run 35 and replicates are shown in black. 4.5.c : average number of households through time for Run 1 and replicates, and Run 35 and replicates, shown over blocky histograms representing the empirical population estimate for the simulation area. 4.5.d : average annual potential maize productivity for the simulation area.

To further illustrate the global dynamics, we graph results in Figure 4.5 for two contrasting parameter sets: Run 1 and replicates (maximum simple group size=50; *s*=.02, β=.1,

μ=.1), and Run 35 and replicates (group size=100; *s*=.05, β=.9, μ=.5). Initially, Run 35 generates larger average group territories (Figure 4.5.a), perhaps because its higher taxation rates fuel expansion, but eventually its higher fatality rates from warfare (and perhaps, too, the toll of higher taxation; Figure 4.5.b) suppress both population (Figure 4.5.c) and average group territory size (Figure 4.5.a). In both parameter sets, warfare is relatively rare in the first two centuries (Figure 4.5.b), since groups have room to grow without confronting others. Under Run 1 parameters, warfare (and its fatalities) more or less stabilize in the 9th century, whereas under Run 35 parameters, warfare and fatalities increase through the 1000s, after which they vary around fairly high values. Periods of poor production (e.g., around 900, 1000, and in the mid-1100s) tend to decrease deaths from warfare in both parameter sets, presumably because groups are not growing and therefore come into competition less frequently. Somewhat counterintuitively, periods of poor production that are relatively short (Figure 4.5.d) also tend to increase territory sizes (or set the stage for its increase immediately upon recovery). This appears to be the joint result of revolts being less common or less likely to be successful, and mergers being more common. In short, changes in productivity can destabilize polities for several different reasons, especially since productivity changes may not be completely simultaneous or of the same magnitude in nearby locations.

To illustrate how revolt affects the composition of groups we display the (aspatial) composition of the complex groups present in four periods in Run 1 (Supplemental Figure 5). Between A.D. 1020 and A.D. 1060, for example, the remnants of a revolt can be seen in the polity that is led by group 79. At the tail of this complex group, group 224 is subordinate to group 74. In A.D. 1020 group 74 is subordinate to group 248, yet group 74 revolts multiple times, each time then becoming subordinate to different dominants.

Since the dynamics of complex groups depend on total agent population, the next set of analyses concentrates on Run 1 and its replicates, which best fit the empirical populations. We calculated the territory size for each group at its highest organizational level at the last year in each of the 14 periods used to calculate empirical populations. That would be the simple group size for groups not subsumed in a complex group, otherwise we summed the territory sizes of each of the simple groups within each complex group. With the tools used for the kiva and settlement sizes we can then determine whether group territories through time correspond more closely to power-law or log-normal distributions. This is especially valuable because we understand the nature of the processes driving complex group size in the simulation, which includes an important role for dynamics of the "biggest-get-bigger" sort (Supplemental Figures 4.6 and 4.7).

Simulated territory sizes are log-normally distributed until the 980–1020 period (Table 4.4). At that point they begin to correspond to a power-law distribution, with some variability at the test-statistic level until strongly returning to a log-normal distribution in the final 1260–1280 period. This is precisely what we would expect if the power-law distributions are generated by the advantages in competition that larger groups come to have in the context of relative scarcity of agricultural land as populations grow.

Table 4.4. Summary of conformity of simulation territory-size distributions to power-law expectations, evaluated in the last year of each of the empirically derived periods. "Power-law probabilities" between 0.1 and 1 indicate inability to reject the hypothesis that the data could have been generated by a power law. "Compare distributions" values of 0.6 to 1 indicate a power-law; values from 0 to 0.4 indicate a log-normal distribution; intermediate values are ambiguous. Positive values for the "Test statistic" indicate power-laws; negative values indicate log-normal distributions.

year	alpha	power law stat	Compare distributions	Test statistic
725	1.291	0	0.042	-1.728
800	1.207	0.01	0.121	-1.169
840	1.202	0	0.164	-0.978

880	1.188	0	0.010	-2.343
920	1.178	0	0.010	-2.315
980	1.176	0	0.089	-1.346
1020	1.202	0.83	0.614	0.290
1060	1.181	0.19	0.570	0.177
1100	1.183	0.93	0.556	0.141
1140	1.182	0.23	0.427	-0.185
1180	1.193	0.81	0.613	0.288
1225	1.203	0.44	0.420	-0.203
1260	1.181	0.3	0.428	-0.182
1280	1.191	0	0.037	-1.781

Discussion

We proposed that log-normal distributions may result from many different processes whose effects are roughly proportional to the size of entities in the previous time step. For log-normal distributions there is no signal that size itself is disproportionately advantaging further growth. Distributions corresponding to power laws, on the other hand, typically result from processes in which the largest entities in the previous time step are the most likely to grow even larger, as we might expect when power disparities or other advantages to size exist.

In Table 4.5 we summarize the outcomes of the analyses from Tables 4.1–3 by classifying these as corresponding to a power-law, corresponding weakly to a power-law, corresponding to a log-normal distribution, or, finally, of ambiguous status. To be characterized as corresponding to a power-law a distribution must exhibit a power-law statistic of greater than 0.2, a compare distribution statistic of greater than 0.6, and a test statistic of greater than 0.5. If a distribution is characterized as weakly corresponding to a power-law its power-law statistic is above 0.1, its compare distribution statistic is between 0.4 and 0.6, and the test statistic is between 0 and -0.1. For a distribution to be characterized as log-normal, it must have a power-law statistic below 0.2, a compare distribution statistic of 0.4 or less, and a test statistic less than -0.5. Distributions classified as ambiguous may have a weak power-law statistic with the other statistics indicating a power-law, or a strong power-law statistic while the other statistics strongly indicate log-normality.

Table 4.5. Summary of analysis results for empirical and simulated distributions.

Years A.D.	NSJ Kiva sizes (empirical)	MSJ Kiva sizes (empirical)	CCP Kiva sizes (empirical)	VEPIIN Settlement Sizes (empirical)	VEPI Territory Sizes (simulated)
600–725				power-law	log-normal
725–800				power-law	log-normal
800–840				power-law	log-normal
840-880				power-law	log-normal
880–920				power-law	log-normal
920–980	Weak power-law	Weak power-law	power-law	power-law	log-normal
980–1020				power-law	power-law
1020–1060				ambiguous	power-law
1060–1100				ambiguous	power-law
1100–1140				power-law	weak power-law
1140–1180	Weak power-law	Weak power-law	power-law	power-law	power-law
1180–1225				ambiguous	weak power-law
1225–1260				weak power-law	weak power-law
1260–1280				power-law	log-normal

In our view, the general convergence of empirical distributions of kiva and settlement sizes on power laws during PII times strongly suggests a consolidation of power into one or more multi-village hierarchies. The fact that the territory-size distributions generated by the simulation are similar further suggests that the processes we model—in which larger settlements and larger groups are advantaged by receiving flows of tribute, and by their ability to prevail in conflicts and subsume smaller groups—were also active in the prehispanic social settings of interest. The power-law signal in all three data streams is substantially weaker during the PIII period, which we take to suggest less highly structured organizations, with more power devolving to local centers. These themes are explored more below.

Pueblo II Consolidation of Power

The primacy of Casa Rinconada in our studies, as well as the results of distributional analyses pointing unambiguously to power-law structure for the Chaco core and periphery, support the (non-controversial) notion of the CCP, and Chaco Canyon in particular, as a central place for ritual for the greater Southwest in the PII period. If our scaling logic is approximately correct, Casa Rinconada could have accommodated one or two representatives of each great kiva community in the far-flung population of outliers.

When we look to settlement sizes in the VEPIIN study area (resolved at a finer temporal scale than the Pecos periods to which the kivas are assigned) we see evidence of both power-laws, and ambiguous probabilities. One of the ambiguous periods, from 1060–1100, is precisely at the point when the Chaco great house pattern is first superimposed on the central Mesa Verde (Lipe 2006). Our settlement data suggest that Chacoan influences, whatever their nature, had not completed their structuring work in the central Mesa Verde (VEPIIN) region until the 1100–1140 period, and continued to prevail through 1180 even if new great houses were not being built.

After producing log-normal territory distributions from 600 through 980, simulated territory-size distributions turn solidly towards power laws from 980 through 1100, after which they alternately exhibit power laws or weak power laws until 1260. Figure 4.6, top panel illustrates a slow increase in the average territory size of groups—for Run 1 and replicates at least—through the 1000s and 1100s, until almost 1200. Since simple group size in these runs is capped at 50, this growth is through the process of chaining ever more simple groups into ever fewer large complex groups. This process is ultimately driven by generally high productivity during these times fueling population growth, expansion of complex groups through addition to their territories via warfare and merging, and successful resistance of revolt.

Although the processes in the simulation are complex, they are understandable, and the key to the appearance of power-law distributions in their territory sizes is that (all other things equal) large groups have an advantage over small because they can conquer or subsume them. Growth happens for those that are already large, within limits set by the productivity of dry-farming maize (explicit and endogenous in the simulation) and transport costs for people and materials (partially represented in the simulation). Within complex groups, simple groups pay tribute to their dominant groups, with tribute passing through to the highest dominant group in the hierarchy.

Analogies between the processes in the simulation and those in the archaeological record should be sought at a fairly high level of generality. In the real world, a growing polity might not have to come to blows with each of its neighbors, or threaten to do so, to expand its influence and power. Flows of tribute in maize in the simulation might, in the reference societies, materialize as contributions to centralized feasts. Mounting evidence shows that Chacoan great houses hosted feasting events that brought visitors carrying food and ceramics from elsewhere (Cameron 2009; Harris 2015; Windes 1987). Often "potluck" in nature, such feasts could be seen as a type of tribute to the ritual power of central places. (Mahoney and Kantner [2000:10] do explicitly argue for tribute flow within the Chacoan system.) Such "doings" (Fowles 2013) reinforced the hierarchies materialized in the fabric of great houses and great kivas, much as "memory of [their] social construction probably provide[d] one of the most important elements of personal identity to groups" (Earle 2001:27).

It has long been understood, too, that the construction of Chaco's great houses would have required flows of labor from outside the canyon; that a highly significant proportion of the ceramic vessels and lithic raw materials used at Chaco came from the Chuska area (Cameron 1997; Toll 1991); that those great houses were built mostly from non-local timbers (Reynolds et al. 2005); and that in fact much maize probably *did* flow into Chaco Canyon from its periphery (e.g., Benson 2010). Those uncomfortable with the idea of tribute can mentally substitute such flows whenever we use the more general term! Of course, what appears as a strictly political process in the simulation would likely be of inextricably mixed social, ceremonial, and political valence in this society (Earle 2001:27; Fowles 2013; Heitman 2015). From initial advantages to virtual simple groups controlling lands allowing them to grow more rapidly than their neighbors, who they came to dominate, to the long chains of dependencies grown in the simulation, in Pueblo society ritual and ceremony provided both a rationale for the wielding of power, and an important means for wielding that power.

Pueblo III Reorganization and Depopulation

The characterization of group sizes in kivas does not change markedly between the PII and PIII periods except for the disappearance of the mid-sized court kiva in the CCP (they were never common in the other two areas), though the largest kivas decrease in size and number and the sample size of all kivas decreases everywhere, but particularly in the CCP (Supplemental Table 1). During PII times in the Chaco core/periphery, the largest kiva, Casa Rinconada, might accommodate some 130 people, while during PIII the largest kiva, the Chacra great kiva, likely accommodated 70-some participants. Aside from Chacra, CCP PIII kivas are quite small, with modes around 12 and 25 people. Both the decrease in kiva number and size support the dissolution of Chaco as the preeminent center.

In the NSJ, while great kivas continue to be used throughout PIII, the increase in smaller kivas (Figure 4.2b) may suggest a reorganization of ritual. This, coupled with the increase of plazas and multi-walled structures as central places, may indicate a switch from global (Chacoan) ritual, to more local ritual serving single communities or relatively small groups of communities. Our settlement data suggests, though, that this restructuring took place mostly after 1180. Perhaps the hierarchy that persists after that date is less pan-regional or regional, and more local in nature: multiple competing groups rather than one large and connected complex. The proliferation of towers among the VEPIIN settlements after 1140 and of multi-walled structures after 1225 may suggest development of leaders extracting tribute at fairly local levels to build these walls and towers (of course, their construction could have been the tribute). In support of this idea, the complex groups in the simulation react to the generally low productivity in the thirteenth century with decreases in size (Figure 5.a).

During the final two decades of occupation the settlement-size distribution again becomes a power-law after 80 years of somewhat ambiguous structure. Perhaps this should be regarded as revealing a structural backbone that remained after the departure of those not in settlements organized in terms of the hierarchy that the last-to-leave settlements represented.

Our results show that interpretations of Ancestral Pueblo people as being egalitarian or hierarchical depends on when we look, and also on where we look. If we define our scale of inquiry to encompass all kivas, and not just (say) household kivas, coincident with the rise of Chaco we see increasing numbers of large kivas capable of enticing many individuals into integrative rituals. The largest great kiva, Casa Rinconada at Chaco Canyon, of a type completely different from the household kivas, stood at the apex of a polity with Chaco at its core. Similarly, the largest settlements in the PII period attracted people from smaller settlements through the processes required by staple finance (Earle 2001) organized by ritual practice, but—we suggest—ultimately backed by threat of force.

The simulation takes the puzzling archaeological record for Chaco and the system it organized and exposes candidate mechanisms for producing this structure. Individual households interact with their local landscapes and with other local households, forming groups that cooperate more or less successfully through public goods games and protect their territories as best they can; those that are fortunate enough to land on the most productive soils reproduce the best. Particular lineages perpetuate themselves and as they grow may gain additional power by encompassing other such groups in large polities. The settlement-size scaling locates settlements within their regional and temporal context; kiva scaling examines how households and communities may have interacted in a ritual hierarchy; and the version of the Village simulation exercised here demonstrates how the emergence of local leadership facilitating cooperation for defense of arable land and producing other public goods, and structured tribute flow from subordinate to paramount groups, can stimulate and perpetuate hierarchical relationships resembling those reconstructed for the Chaco system.

One main reason that the archaeological record of Chaco is puzzling—clearly recognized by Earle (2001)—is that Chaco looks like a staple-financed organization, but the usual conditions for staple finance include a highly concentrated productive environment surrounded by unproductive areas, such as an irrigated river valley in a desert, causing circumscription. In such systems the costs of forcing households to contribute to a polity are very low, given their extremely limited outside options. The more extensive dry-farming that dominated maize production in the "dry-farming millennium" from AD 300–1300 (Kohler 1993) is not so obviously conducive to controlling households and their communities.

But the places where dry farming could be successful on the Colorado Plateau in the years represented by the Chaco system were in fact rather limited (Bocinsky et al. 2016:Fig. 6D–F). More importantly, those areas were full—or at least that is a plausible inference based on the Southwest-wide sensitivity of life expectancies and birth rates to climatic fluctuations beginning around AD 1000 (Kohler and Reese 2014). (Earlier, a less-packed maize-growing niche allowed households to escape climate-driven downturns in maize production through mobility, largely shielding their demographic rates from this variability.) Populations, through growth, circumscribed *themselves*, and it remained only for a polity to point this out, guaranteeing in the process that member groups need fear nothing from their neighbors in return for supporting the polity. This, however, is a fragile basis for coercion, as it depends on both the credibility of a ritual system claiming to underwrite production, and the center's ability to support threatened member groups through manipulation of a complex set of debts, allegiances, force, and threats of force. It is perhaps more marvelous that it was able to endure for four-to-five generations, from about AD 1030–1140 in its fullest expression, than that it didn't last longer.

Conclusions

For some time southwestern archaeologists have been aware that hierarchies of site size, great house size, and kiva size are visible for significant spans of time in significant portions of the Pueblo world. We likewise understand that these must imply some hierarchical organization of practices connected with these structures. More recently, we have learned that variability in community center size (in the central Mesa Verde region at least) is only weakly connected with the potential maize productivity of their catchments, inviting other, complementary explanations for this variability.

What we add here is, first of all, some tools drawn from the analysis of complex adaptive systems that allow size distributions to be characterized in ways that suggest their generating processes. We acknowledge that these tools do not, for our data, always render clear and concise verdicts, but they have provided useful hints as to the directions in which we should look for the generating processes.

Second, we have briefly described and exercised a model that implements a set of processes widely considered to be universal (e.g., Johnson and Earle 2000)—population growth, competition, and polity growth through conflict or threat of conflict generating flows of tribute of various sorts to dominant groups—that demonstrate one pathway by which size can generate further growth, within limits ultimately imposed by production, transportation, and communication technologies.

Although we coded it to help us understand how polities might grow, the simulation also provides several potential insights into the perennial problem of why poor production might imperil polities. At the basal level, simple groups shrinking in size might flip from hierarchical to non-hierarchical (see Kohler et al. in review). This, in turn, might reduce (and perhaps destroy) their returns to the public goods game, decreasing or eliminating the flow of tribute upwards in the social hierarchy. Intermediate groups who had been profiting from tribute might shrink too, and perhaps flip in structure. As these processes worked their way up the chain, we can predict that successful revolts would become more common than new acquisitions to complex groups, and even absent successful revolt, complex groups could essentially crumble from below. Moreover, smaller remaining polities would be more vulnerable to attack, given fewer subordinate groups. The potential generality of such processes is illustrated by their similarity to the scenario envisaged for the late Bronze Age Argolid collapse by Maran (2009:255–256).

Our results reinforce the likelihood that one or more organizations (called polities here for convenience) existed in PII times and connected village-level communities into regional and (likely) pan-regional networks linked via flows of goods and labor. These results unsurprisingly point to Chaco Canyon as the place of pre-eminence and indirectly reinforce the notion that the decline of its hegemony was connected to conditions for maize farming that were likely markedly poorer in the San Juan Basin in the mid-1100s than in the northern San Juan, where regional systems endured into the PIII period, by which time they would have been influenced by Chaco's remembered example but not controlled by its leaders.

Our analyses also suggest a central role for great kivas (particularly during the PII period) as mechanisms to help reinforce hierarchy. As not every Puebloan could be accommodated for great kiva events, only those so empowered by their groups would attend. Such restricted access—with concomitant benefits for accumulating restricted knowledge—would have helped maintain the local and global hierarchies much as, among contemporary Pueblos, hierarchy is evident in differences between the "ceremonially rich" and the "ceremonially poor" (Ware 2014:41). It appears that representatives of all existing great houses in Chaco Canyon and in "outlier" communities with great kivas could have been (and we suggest were) accommodated in the largest of them all, at Casa Rinconada.

Endnotes

1. 700–890; all dates are A.D./C.E.; Pecos Classification dates from Bocinsky et al. 2016.
2. Ortman (2016:Figure 5.6) demonstrates that in the central Mesa Verde area increasing site area scales against site population in a sublinear fashion, so that larger sites are more dense—a finding that suggests to us that defense was perhaps on average more important in site population growth than provision of areas for large-scale ritual involving populations of other ceremonial centers. The converse is true in the Tewa Basin of the northern Rio Grande in the 15th and 16th centuries: plaza area increases more rapidly than site population as site populations increase. In accordance with this interpretation, levels of interpersonal violence were also notably lower at that time in the northern Rio Grande than in the PII–PIII central Mesa Verde (Kohler et al. 2014).
3. Our identification of modes is visual, not rigorous. Zhou et al. (2005) illustrate a quantitative approach employing spectral analysis.
4. The version of the Village code reported here is archived and under active development on GitHub: https://github.com/crowcanyon/vep_sim_beyondhooperville.
5. Available as a Working Paper at http://www.santafe.edu/media/workingpapers/15-04-011.pdf.
6. Although these limits may seem small, recent research suggests that average community size on Mesa Verde in any period never exceeded 26 momentary households, with the largest community, forming in the 1260–1280 period, estimated at 76 households (Reese 2014).

*Acknowledgements***.** This paper utilizes extensions to the "Village" ABM, originally developed with support from the National Science Foundation (BCS-0119981, DEB-0816400), which also generated and organized the empirical data on site sizes we use here. We thank the Templeton Foundation for funding part of this research. Our numerous colleagues in the Village Ecodynamics Project, as always, have provided much assistance and inspiration. Aaron Clauset, Matt Grove, Marcus Hamilton, Paul Reed, Ruth Van Dyke, and Tom Windes also provided useful advice. Crabtree acknowledges support by NSF Graduate Research Fellowship DGE-080667, an NSF GROW fellowship and a Chateaubriand Fellowship. This paper is dedicated to the memory of Robert P. Powers, not just a fine friend but also, among many other achievements, the researcher providing the first useful estimates for Chaco Great House sizes across a broad portion of the Pueblo area.

CHAPTER 5: A COMPLEX ANALYSIS OF ANCESTRAL PUEBLO FOOD WEBS

While the next chapter in this dissertation does not employ agent-based modeling, it uses other tools from complexity science to examine how the actions of individuals had effects on the overall ecosystem of the Ancestral Pueblo Southwest. This chapter uses foodweb analysis as a way forward in understanding the interactions of species within the Four-Corners area. I and three coauthors specifically model human use of the environment to understand the cascading effects of overpredation of species. This study rivals chapter four in complexity; while it does not employ an agent-based model, which requires hundreds of hours of programming and data analysis, the compilation of data for the analyses in the following chapter took hundreds of hours. And while the food webs model does not include any 'moving parts' (such as the agent-based models presented above), the network analyses employed provide a means for examining how different species interact through time. Trophic analysis is a powerful tool for studying the (sometimes-invisible) interactions among species, and is the most robust method for understanding the effects of the removal of species from ecosystems.

Recent applications of trophic analysis have integrated humans into food webs, demonstrating that humans are a part of, and not apart from, ecosystems. For example, Maschner et al. (2009) show that culling sea lions skins for kayaks likely kept the sea lion population low enough to decrease pressure on the Alaskan fishery, while Murphy and Romanuk (2014) have examined, as an opposite side to Maschner's study, how human disturbances negatively affect species richness. These two studies demonstrate how humans can either be cultivars of richness (e.g. Maschner et al 2009), or destructors of biodiversity (Murphy and Romanuk 2014).

Ecosystems without humans are almost nonexistent worldwide, so understanding how humans interact with, modify, and are in turn affected by their ecosystems is important for a comprehensive understanding of both past and present societies and environments. Only through an understanding of how predation and species use effects the availability of preferred human foods can we begin to understand human adaptation in the face of localized climate change.

In the following chapter we analyze the largest terrestrial foodweb compiled to date, which was created expressly for the work presented here. We analyze food webs in the Ancestral Pueblo Southwest, first creating an overall foodweb from modern and archaeological data, and then parsing the data out to three sites from Pueblo I, Pueblo II, and Pueblo III timeperiods. This paper seeks to place Ancestral Pueblo people within their ecosystems to truly understand how their predation choices may have destabilized local food webs. This destabilization would have affected people living on marginal lands unequally, causing them to rely on starvation foods, and potentially influencing them to migrate out of the four corners region. The complete depopulation of the four corners region may be seen as a way for the Ancestral Pueblo people to remove themselves from an inhospitable ecosystem that they themselves destabilized.

This study has the potential to be used for further analyses in the future. For example, the complete matrix of available prey for Ancestral Pueblos in Pueblo I, Pueblo II, and Pueblo III times could be used in an agent-based model to allow for a more realistic foraging model. Further, the data presented in this chapter is being employed in a worldwide comparative project, analyzing how humans have shaped their environments, and how food webs affected humans through time and across the globe. The realism of this study enables a true characterization of human-mediated environmental change and, coupled with the study in chapter four, further demonstrates both the vulnerability of Ancestral Pueblos to environmental shifts, and their resilience in innovating new methods to deal with uncertainty.

Cascading Effects and Social Consequences: Food webs in the Ancestral Pueblo Southwest

Authors
Stefani. A. Crabtree,[1,2]* Lydia J. S. Vaughn,[3] Nathan T. Crabtree[4]

Affiliations
[1]. Washington State University, Department of Anthropology
[2]. Université de Franche-Comté, Maison des Sciences de l'Homme
stefani.crabtree@email.wsu.edu
[3]. University of California, Berkeley
[4]. United States Forest Service

Abstract

For the past century archaeologists have been asking why the Ancestral Pueblo people left the northern Southwest so swiftly and completely in the A.D. 1200s. Reasons for the depopulation have rested on both environmental and social causes, or more recently a combination of the two. Here we suggest that depopulation is caused by the interaction and feedback between social strategies and environmental change. In this paper we examine key prey species in archaeological assemblages, arguing that changing species composition would have had cascading effects on the environment. This, coupled with natural climatic fluctuations and anthropogenic environmental change increasingly made the Four Corners area of the U.S. Southwest less productive for farming and wild-game procurement. We combine a diachronic examination of multiple archaeological assemblages with a database of every modern non-invasive species and their feeding links in a 4,600 square kilometer area of southwestern Colorado. We see increasing aridification through the disappearance and appearance of four key species: elk, snowshoe hare, scaled quail, and Sandhill crane. Although human omnivory provided some resilience to environmental change, a decrease in key prey likely contributed to decisions to leave the Four Corners area.

Introduction

After seven centuries of successful farming and habitation (Kohler and Varien 2012; Schwindt et al. 2016), the Ancestral Pueblo people completely abandoned the Four Corners area circa A.D. 1300. For over a century, archaeologists have been examining the question of why this abandonment occurred. A consensus has not been reached as to the causes of this depopulation, with explanations resting on environmental causes such as drought (e.g. Badenhorst and Driver, 2009; Douglass 1929; Flint-Lacey, 2003; Schoenwetter and Dittert, 1968), social causes such as violence (LeBlanc 1999), or more recently a combination of the two (e.g. Glowacki 2015; Nelson and Schachner 2002; Ortman 2012).

Recently, researchers (e.g., Bocinsky et al. 2016; Schwindt et al. 2016) have revisited this question with new tools and approaches that look to overarching climate patterns as potential drivers of depopulation. Yet these papers do not take into account how overuse of the environment would have itself destabilized animal and plant populations creating new microclimates. This paper revisits the debate on the depopulation of the central Mesa Verde utilizing modern tools to examine the extent to which anthropogenic change destabilized the northern Southwest, making migration essential. This study re-examines this longstanding question using a tool rarely (and only recently) used in archaeological studies: food web analysis (e.g. Dunne et al 2016). We ask how the interactions between environmental and human systems influenced ecosystems in the Four Corners region, and whether such feedbacks between environmental and social pressures may have precipitated abandonment. In contrast to more traditional archaeological methods (e.g. Badenhorst and Driver 2009) we use a food web framework to examine archaeological assemblages from three periods, Pueblo I (A.D. 750-900—Grass Mesa Pueblo), Pueblo II (A.D. 900-1150—Albert Porter Pueblo) and Pueblo III (A.D.

1150-1300—Sand Canyon Pueblo). This diachronic approach allows us to identify changes in species presence and prevalence through time, an important indicator of ecosystem shifts (Parmesan 1996; Parmesan et al 1999). The use of archaeological food webs enables us to focus on species that directly affect humans within the context of the overarching food web, thereby directly examining feedbacks between humans and the environment and clarifying interpretations of the Ancestral Pueblo ecosystem.

While traditional studies enable an understanding of feeding links, the power of food web (i.e., trophic) studies lies not just in documenting presence of species but also in examining linkages among predators and prey. By studying the network topology of trophic webs, it is possible to identify important structural properties that promote stability or increase vulnerability of the web (Tecchio et al. 2013). Moreover, food web approaches are the only means to analyze the effects of species removals and introductions on the other species and links in the web (Fritts and Rodda 1998). This study leverages this analytical approach, building on longstanding studies of Four Corners area archaeology, such as those finding that deer depletion forced Ancestral Pueblo people to rely on other protein sources (Badenhorst and Driver 2009; Bocinsky et al. 2012; Cowan et al. 2012; Schollmeyer and Driver 2012). This work additionally adds to a growing body of human food web studies, which will enable comparison of environments worldwide (Dunne et al 2016; Martinez et al 2013-2017).

To date, this study is the largest terrestrial food web compiled. We take the approach of compiling a large database of feeding links for all known species in the Four Corners area, creating full-scale trophic webs to examine how humans were connected to the greater Four Corners ecosystem through time. This paper shows that human use and modification of the landscape dramatically changed the environment of the Four Corners region during occupation, destabilizing the ecosystem, influencing the development of new strategies, and precipitating depopulation through three main findings:

- Food web analysis provides new evidence for feedbacks between anthropogenic environmental impacts and their subsequent effects on humans.
- Aridification and human-mediated deforestation are visible in the archaeological record through the disappearance of two woodland-dependent species and the appearance of two grassland-dependent species over time.
- When human density is low, omnivory allows humans to be resilient to environmental fluctuations, whereas when human density is high, the availability of key prey decreases, and humans must rely on other means of survival, such as migration.

Studying trophic interactions to inform understanding of environmental and social change

Food web studies aim to understand species interactions in a defined environment by mapping the network of predator-prey relationships (trophic networks). Computational approaches to studying these trophic relationships enable the use of large datasets to investigate individual inter-species interactions and how changing interactions can cause cascading system-wide changes. Understanding how species losses affect food webs (Dunne, Williams and Martinez 2002a; Srinvansan et al. 2007), identifying commonalities among food web structures (e.g. Dunne, Williams and Martinez 2002b; Stouffer et al. 2005; Williams et al. 2002), and determining how individual species interactions cascade across trophic levels (Micheli et al. 2005) has advanced our understanding of compex ecosystem structures and dynamics.

Within a food web, each species is assigned a trophic level, representing how organisms of that species obtain energy and carbon. At the basal trophic level, primary producers generate biomass from inorganic materials (e.g., plants photosynthesize). With increasing trophic level, primary consumers eat primary producers, secondary consumers eat primary producers and primary consumers, and so forth up to apex predators, which consume prey residing at high trophic levels (see Bonhommeau et al. 2013). By tallying the complete set of species historically eaten and used by humans, and then connecting those species to other species they consumed (and are consumed by) we can evaluate human resilience to environmental fluctuations. Using trophic webs constructed from distinct time periods, we can identify species introductions and local extinctions through time and calculate their effects on food web properties, thereby better understanding how humans were interconnected to the greater environment and how this connection evolved and fluctuated through time.

The American Southwest

The northern U.S. Southwest is unique for archaeological inquiry. Preserved wood from Pueblo structures permits dendrochronologists to pinpoint when sites were built and abandoned, while the semi-arid climate helps preserve faunal remains (Nash 1999). This high degree of preservation coupled with relative precision of demographic reconstruction means that archaeological food webs can be examined at multiple sites from multiple time periods and placed in their correct regional demographic context. The ability to synthesize information across timescales provides a powerful way to relate incremental changes to cascading environmental consequences. By studying how anthropogenic changes such as deforestation, soil erosion, or harvest pressure coincide with the distribution of flora, fauna, and human populations in the region, and how these changes likely led to social strategies, we can better understand the depopulation of the central Mesa Verde region.

The area used in this study is in the Central Mesa Verde Region and the Village Ecodynamics Project's (VEP) northern study area (Figure 5.1). The VEP is a multi-disciplinary project aiming to understand the prehispanic Pueblo occupation of the Four Corners area through empirical research and modeling. The 4600-sq-km northern VEP study area supports seven biotic communities--sagebrush, grasslands, pinyon-juniper woodland, gambel oak scrubland, pine/Douglas fir forest, spruce/fir forest, and alpine tundra (Adams and Petersen 1999:15)--and encompasses the "Great Sage Plain" (Newberry 1876), parts of Canyons of the Ancients National Monument, and the Mesa Verde landform (Figure 5.1). This area is a diverse ecological zone encompassing some of the most densely populated areas of the Ancestral Pueblo occupation (Hill et al. 2010; Schwindt et al 2016). This study focuses on three sites, Grass Mesa Pueblo, Albert Porter Pueblo, and Sand Canyon Pueblo, all of which had roughly equal access to these seven biotic communities.

We focus our study on maize farmers living during the Pueblo I (A.D. 750-900), Pueblo II (A.D. 900-1150), and Pueblo III times (A.D. 1150-1300, Table 5.1). During this time the inhabitants of the area were maize farmers who supplemented their calories by hunting deer, rabbits, and later domesticating turkey. Briefly, Pueblo I times are marked first by population growth indicative of a Neolithic Demographic Transition (Kohler and Reese 2014) followed by population decline at the end of the Pueblo I period. High rates of local population growth recommenced during the mid-Pueblo II period (Schwindt et al. 2016), ultimately reaching about 27,000 people in the mid-A.D. 1200s (the finale of Pueblo III), a level more than twice that reached during the Pueblo I peak. Throughout the history of occupation of this area, people moved from dispersed hamlets to relatively dense villages (Crabtree 2015). The density of habitation combined with the high level of population would have had dramatic effects on the environment, including clearing vegetation for habitations and fields, burning vegetation to increase hunting opportunities, and hunting large quantities of animals to feed the growing population.

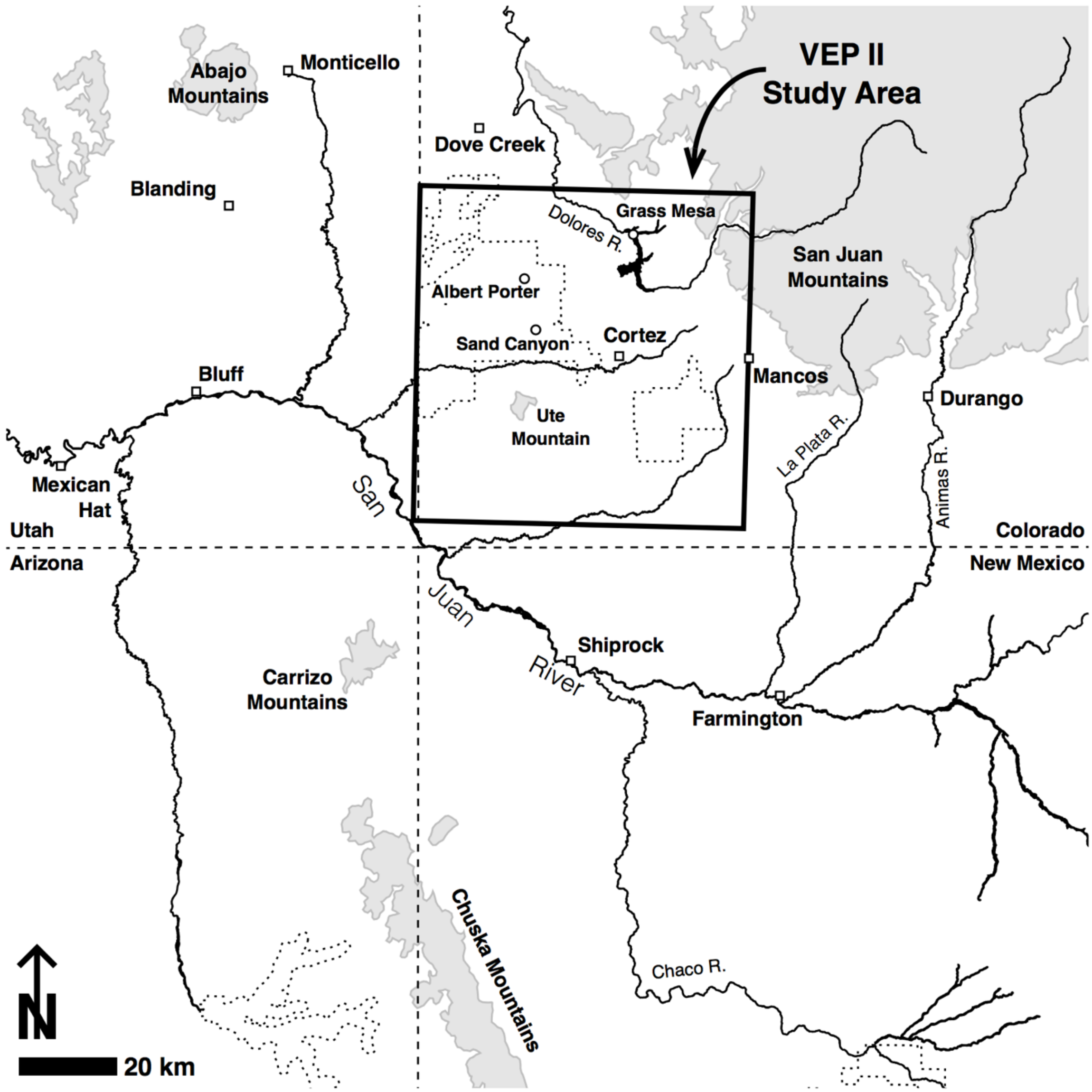


Figure 5.1. Central Mesa Verde area; box shows study area used for this research. Sites used for analyses in this paper (Grass Mesa Pueblo, Albert Porter Pueblo, and Sand Canyon Pueblo) represented by circles. Figure courtesy of R. Kyle Bocinsky.

In this study we pay particular attention to environmental changes due to farming and effects of environmental change on farmers, since 70 to 80% of the diets of Ancestral Pueblo people was composed of maize (Decker and Tiszen 1989; Coltrain and Janetski 2013). In spite of a range of known human-environment interactions, it is tempting for archaeologists studying early farming populations to set these farmers apart from many environmental pressures; our work addresses these oversights. The invention of agriculture arguably made humans less reliant on the unpredictable nature of foraging, but it brought a host of other challenges. Many of the known effects that Ancestral Pueblo people had on the environment, such as deforestation and erosion, are directly related to clearing native vegetation for fields for farming maize (Kohler 2004).

Table 5.1. Periods and Sites examined here.

Years A.D.	Cultural Period	Description
Prehistory to 500	Paleoindian/Archaic / Basketmaker II	No sites in this study
600 to 750	Basketmaker III	No sites in this study
750 to 900	Pueblo I	Grass Mesa Pueblo
900 to 1150	Pueblo II	Albert Porter Pueblo
1150 to 1300	Pueblo III	Sand Canyon Pueblo
1300 to 1500	Pueblo IV	No sites in this study
A.D. 1500 to present	Colonial period	Modern data used to understand species composition

Clearing of forests for agricultural fields changes the functioning of ecosystems (Diaz and Cabido 1997; Wardle 2011). Changes in plant cover can change carbon and nitrogen cycling (Wardle et al. 2011), influence water availability and local and regional climate (Jackson et al 2009; Bala et al 2007; Gehlhausen et al. 2000), and affect organisms at all trophic levels (Knops et al 1999; Schmitz et al 2000). In the Four Corners region, forest clearing in favor of intensive farming of maize, beans and squash likely affected the local environment in this manner.

Sediment cores from Prater Canyon, an intensely inhabited canyon in the northeast of Mesa Verde National Park, show intensive burning episodes during occupation, suggesting that

Native Americans used fire to modify landscapes (Herring, Anderson and San Miguel 2014); maize, the primary crop of the Ancestral Pueblo people, is a notoriously nitrogen-greedy plant that would have thrived on the short-term increase in nutrients mobilized by these fires (Benson 2011; Wan et al. 2001). Fire also may have been used as a tool for hunting, creating ecosystems that were more favorable for Ancestral Pueblo people to pursue game. Elsewhere, scientists have shown that repeated landscape burning and planting of nitrogen-greedy crops reduces long-term soil fertility (Monleon et al 1997), which may have occurred over time in the ecosystem reported here.

Another known effect of maize farming on the greater Four Corners environment is erosion. It is noted that the Ancestral Pueblo people living in Mesa Verde applied checkdams by the 1200s to improve the short-term productivity of their fields (Kohler 2004; Rohn 1963). While these efforts would have decreased erosion in the short-term, the rapidly growing population may have outstripped the ability of these measures to alleviate long-term effects (Herring et al 2014; Kohler 2004:225).

Plant species were not the only species to be affected by human arrival. While Ancestral Pueblo people depended on rabbit and hare for protein after deer depression, they also domesticated turkey, feeding them from their maize storage (Rawlings and Driver 2010). Keeping turkeys thus caused Ancestral Pueblo people to clear more land, creating a more open landscape. The combination of field clearing (which would remove trees as well as other native flora and drive out pest species, preferred prey, and large predators) with the introduction of domesticated turkey (which would intensify field clearing for more maize gardens), and the introduction of the domesticated dog (which likely chased out many other species) likely created zones of habitation devoid of native flora and fauna, potentially causing crowding of native species on the periphery (Urban 2015).

The story of Ancestral Pueblo people unfolds on a changing landscape with occasional severe droughts that are independent of human actions. Human actions made some of these conditions worse (e.g. erosion) and enhanced the presence of some species on the landscape (e.g. rabbits). Below we first discuss important species presences/absences observed when compiling the food web database. Second, we consider properties of a reconstructed composite food web for the entire Four Corners area. Finally, we present network metrics derived from specific archaeological assemblages: Grass Mesa Pueblo, a Pueblo I village, Albert Porter Pueblo, a Pueblo II village, and Sand Canyon Pueblo, a Pueblo III village. Methods are detailed at the end of the paper. The trophic webs presented below derive from large, well preserved samples excavated using a consistent set of practices that should approximate a complete set of human prey species.

Materials and Methods

Data for this article were collected in a 4,600 square kilometer area in southwestern Colorado that overlaps some of the densest archaeological habitations in the American Southwest and corresponds to the Village Ecodynamics Project II's northern study area (Figure 5.1). We identified every plant and vertebrate animal within this study area and catalogued them in our database; invetebrate data is coarse-grained to the order level. Within this area, modern vegetation cover was downloaded from the U.S. Soil Survey or from U.S. Forest Service reports. Initial vertebrate data was compiled from Mesa Verde National Park's database on animals that live in the park. Further data per animal class is defined below.

Data were compiled from trusted online field guides to ensure that future users could easily access background information on species. Avian data was compiled from the Cornell Lab of Ornithology, amphibian and reptile data from the Fieldguide to Reptiles of Arizona and mammal data from the University of Michigan Museum of Zoology. If a species was not represented in the preferred online field guide, either a) species data was found at another reliable source, such as the Audubon Society, or b) a similar species was identified and its data was used. For example, Hammond's spadefoot toad prey data was not found on any reliable site, so data for the plains spadefoot toad was substituted. The avian data was crosschecked by an expert to ensure that all species were accounted for and that vague diet descriptions were properly coded.

Each species is numbered from 1 to 334 to give it an individual identifier. Species were then individually researched according to reliable sources, as described below. Verbal data on specie consumption patterns was compiled in the database as presence/absence. For example, the long eared myotis is described as preying "mainly on moths, but their diet also includes beetles, flies, and spiders." In compiling the matrixes for our analysis we noticed several species from archaeological assemblages that were not present in modern data, or that were present in modern data but not the archaeological data; both of these were included to create a complete database of organisms. To create the overall food web we include all species that were characterized in the matrix and all of their feeding links. This gives us the inferred species that humans would have interacted with throughout the four-corners area.

When we pared down our analyses to the individual archaeological assemblages, first we created a matrix of all human prey, (e.g., humans→ deer) corresponding to their temporal assignment. Then the prey species of the primary prey of humans were added to the matrix (humans→ deer → herbaceous grasses). Predators of the primary prey species of humans were also added to the matrix (wolves→ deer). Thus these webs represent those species that would be directly affected by human intervention. This means many nodes will be represented, but not all links might be represented. Webs with high connectance (the realized proportion of possible links among all species; Cockburn et al. 2012) show much higher complexity, while those with low path-length (the number of edges it takes to connect all nodes) are likely to be connected in a small world network (all nodes are connected to all others; Crabtree 2015; Dunne, Williams and Martinez 2002b). Understanding the distribution of links in the web can have important ramifications for understanding extinction events (since redundancy of species makes webs more stable—Yeakel et al. 2014), the vulnerability or resilience of the overall food web, and for understanding how invasive species will link in with the web (Dunne, Williams and Martinez 2002a).

The assemblages in the archaeological food webs are smaller than in the composite food web, potentially influencing the decreased clustering coefficients seen in the analyses below. The high percentages of excavation in each of these sites suggest, however, that it is not sampling bias but rather a real signature with the smaller assemblages. The database for this project is available at https://wsu.academia.edu/StefaniCrabtree, which indicates data sources and the 334 species identified in this project.

Choice of sites

One well-excavated site per period (Pueblo I, Pueblo II and Pueblo III) was chosen for analysis. Grass Mesa Pueblo was chosen because it is one of the largest and most completely excavated Pueblo I villages in the Central Mesa Verde region and was excavated as part of the Dolores Archaeological Project (DAP). The methods developed for the DAP influenced those used by Crow Canyon Archaeological Center who excavated and analyzed Albert Porter Pueblo and Sand Canyon Pueblo. This minimizes any differences among these three assemblages due to sampling or analytical biases. Albert Porter Pueblo was chosen due to it having a large Pueblo II component and being excavated by Crow Canyon Archaeological Center. Albert Porter was occupied into Pueblo III, but only the Pueblo II occupation was used for these studies. Sand Canyon Pueblo was chosen due to being the largest site occupied during Pueblo III times, and being well-excavated by Crow Canyon Archaeological Center.

Excavation techniques

Grass Mesa Village was excavated with shovel, trowel, and backhoe. Deposits were screened through ¼" mesh. (Kohler 1983: 28). Excavations at both Albert Porter Pueblo and Sand Canyon Pueblo were by trowel and shovel, and most deposits were screened through ¼" mesh. (Special features were screened through ⅛" mesh; Ryan 2003; Crow Canyon Archaeological Center 2004.)

Zooarchaeological methods

Zooarchaeological analysis was not performed by the authors of this study, but was compiled from existing archaeological reports. Zooarchaeological methods are outlined in Adams 2015; Badenhorst and Driver 2015; Crow Canyon Archaeological Center 2004; Muir 2007; Neusius and Gould 1988; Matthews 1988.

There are challenges in identifying fauna. In the zooarchaeological studies here, only those species that could be positively identified were catalogued as such; otherwise they were assigned to lump categories such as "large bird" or "large mammal" (Adams 2015; Badenhorst and Driver 2015; Crow Canyon Archaeological Center 2004; Muir 2007; Neusius and Gould 1988; Matthews 1988). Only those fauna that were positively identified were catalogued in the food webs database. Fauna analysis for the Pueblo I site of Grass Mesa Pueblo was performed by Sarah Neusius (Neusius and Gould 1988), fauna analysis for the Pueblo II site of Albert Porter Pueblo was performed by Shaw Badenhorst and Jon Driver (Badenhorst and Driver 2015), and fauna analysis for the Pueblo III site of Sand Canyon Pueblo was performed by Robert Muir following protocol developed by Jon Driver (Muir 2007).

Invertebrates

Invertebrate data, unfortunately, could not be verified at the species level. While charismatic mega fauna have been well studied, most insects in the Southwest have not been studied to the same resolution. After consulting with an expert, invertebrate data was coarse-grained to the Order level. It is hoped that future studies can resolve invertebrates to a more fine-grained level.

Specialists versus generalists

The most important distinction in coding the data was determining if an animal was a specialist or a generalist. This was preserved in coding by not overrepresenting those species that make up a very small proportion of the diet of the animal. For example, the mourning dove is said to gain 99% of its daily food intake from seeds. Consequently, those plants that produce seeds are represented as their prey, while plants that do not produce seeds (but could, conceivably, be a part of the diet when seeds are unavailable) are not represented.

Carrion feeders

Carrion feeders can presumably feed on any dead animal. Animals that had a small portion of their diet as carrion were not presumed to eat every represented animal, but only the named prey was represented (for similar reasons to the above specialist versus generalist concerns). Animals that receive most of their diet from carrion (e.g. turkey vulture) are presumed to eat every animal represented.

Cannibalism

If a key characteristic of an animal was eating its own species it was coded as cannibal. Mammals were not coded as cannibals by default. While suckling does represent a type of cannibalism (young cannot survive without feeding on their mother's milk) we removed this link in this analysis.

Dogs

We include dogs in our food web analyses despite the lack of evidence that humans preyed on them. For one, we know that dogs existed during the occupation of the Central Mesa Verde region, so they must be included in the composite food web for it to be complete. Additionally, domestic dog DNA has been used as proxy for humans when human DNA is unavailable to examine migratory events (Witt et al. 2014). Thus dogs are included in this study. While dogs did enter the Southwest with the earliest Paleoindian migrants, the very high human populations of the Pueblo II and III periods were likely accompanied by a similarly high number of dogs, as is seen in the assemblages we analyze here, and may have expanded the ecological footprint of habitations due to the propensity of dogs to hunt wild resources. Modern packs of feral dogs in the Southwest have been known to hunt deer and pronghorn (ASPCA 2015), and Pueblo dogs in the Southwest likely ate wild birds and rodents in considerable numbers.

Results

Species change as evidence for aridification

The presence and absence of certain fauna can be viewed as indicators of local environmental changes. Here we will discuss four such species whose presence in the species assemblages change through time: elk, snowshoe hare, Sandhill crane and scaled quail. None of these species had many bones recovered, as illustrated in Supplementary Table 2. However, we argue that the presence of these bones in tandem with recent climate studies (Bocinsky and Kohler 2014) indicates an environmental signature.

Elk bones are present in the Pueblo I assemblage, but not later assemblages. Likewise, snowshoe hare were present in the Pueblo I assemblage but were not present in later assemblages, and are not listed as a common species in the guides we consulted. As we discuss below (Discussion), elk and snowshoe hare are both dependent on relatively moist forests for survival. Sandhill crane and scaled quail, however, depend on sparse, dry grasslands for survival. Sandhill crane are present in Pueblo I (NISP 1) and Pueblo III assemblages, yet are not listed as native to the area in the guides we consulted. The modern bird sighting website *ebird*, managed by the Audubon Society, was used to determine modern Sandhill crane sightings in the study area. (Birders use *ebird* to report rare sightings nationwide.) Only 11 individual sightings of Sandhill crane have been reported for the region since 1909 (*ebird*), primarily along the modern Dolores reservoir. While Sandhill cranes are ubiquitous roughly 200 miles to the east in Alamosa, Colorado, their presence is rare in the present study area. Similarly, scaled quail bones are present in the Pueblo III assemblage but not earlier assemblages, and they are not listed as a common species in our study area. Modern scaled quail range does not overlap with southwestern Colorado (Cornell Lab of Ornithology). While scaled quail are common in the Farmington area, roughly 50 miles south of Sand Canyon Pueblo, they have been documented in only two locations within the study area (*ebird*). These are: Mesa Verde National Park (one sighting) and Four Corners National Monument area (one sighting).

The disappearance of two species that rely on woody corridors and high moisture, and the concomitant appearance of two species that do not currently reside in the region and rely on dry grasslands provide evidence of a shift toward a relatively drier ecosystem. Explanations to the shift toward large quantities of elk in the region today, and no scaled quail or Sandhill crane are likely based on modern anthropogenic effects on grasslands being different than those created by Ancestral Pueblo people.

The Composite Food web

We used the compiled trophic database to assemble a composite food web (Figure 5.2). This food web contains 334 nodes representing 298 distinct species (plants and vertebrates) and 36 invertebrate orders. Joining these 334 nodes are 11,344 links representing flows of biomass between consumers (predators) and the species they consume, creating a highly interconnected food web, with many species having overlapping prey. For example, both black-chinned hummingbirds and broad-tailed hummingbirds are represented in the food web, but their primary prey species are the same (Figure 5.2). While other studies (e.g. Yodzis and Winemiller 1999) collapse species into multi-species functional groups, individual species were represented here to illustrate the complete ecosystem of southwestern Colorado. To characterize this composite food web we calculate metrics focusing on the human niche in the food web (Table 5.2).

Predation vulnerability and generality: Predation vulnerability and generality, calculated respectively as the quantity of predators per prey species (Lotze et al. 2011) and the quantity of prey per predator species, characterize the vulnerability of a species to increases in predation and decreases in prey. Humans in the composite web have a low vulnerability score (0.264) showing that they have few predator species, limited to large predators such as wolves and cougars (Table 5.2). The generality of humans in the composite web is high at 3.71. For comparison, the black-billed magpie and common raven, both carrion eaters, are the most general species, with humans as the 27th most general species.

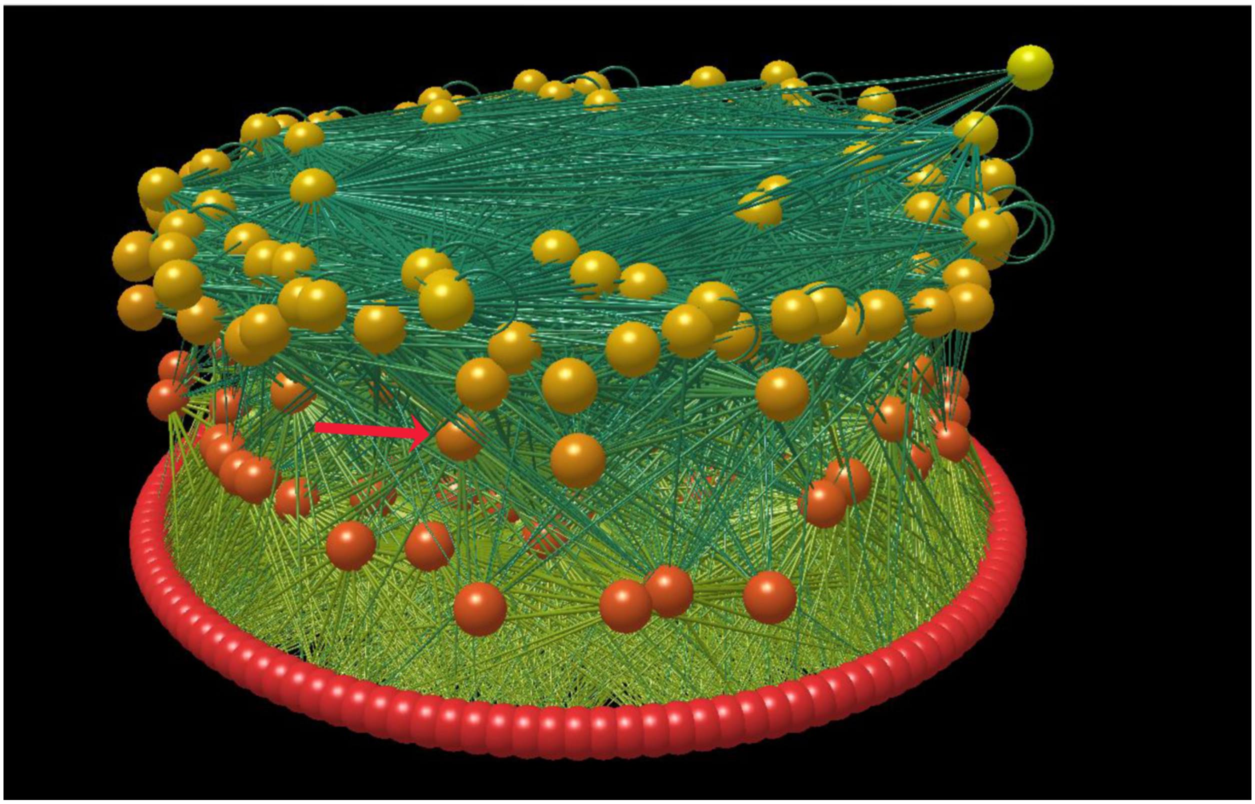


Figure 5.2. Graph of overall foodweb. Trophic level on y-axis. Red nodes indicate primary producers, orange primary consumers, yellow-orange omnivores, true-yellow is true carnivores. Humans pointed at by arrow. The common poorwill, an insectivore, is represented by the node in upper right-hand corner.

The vulnerability scores of the primary prey of humans are reported in Table 5.3 and displayed in Figure 5.3. Unlike humans, the primary prey species of humans exhibit high predation vulnerability. With a score of 2.27, maize is the most vulnerable plant to predation (the only nodes more vulnerable than maize are invertebrates, which may be a reflection of aggregating across many species). Many studies of vertebrate species specifically mention maize as a preferred food source (Sandhill cranes for example, Supplementary Table 1). Many of these animals likely plagued the storage and gardens of Ancestral Pueblo people.

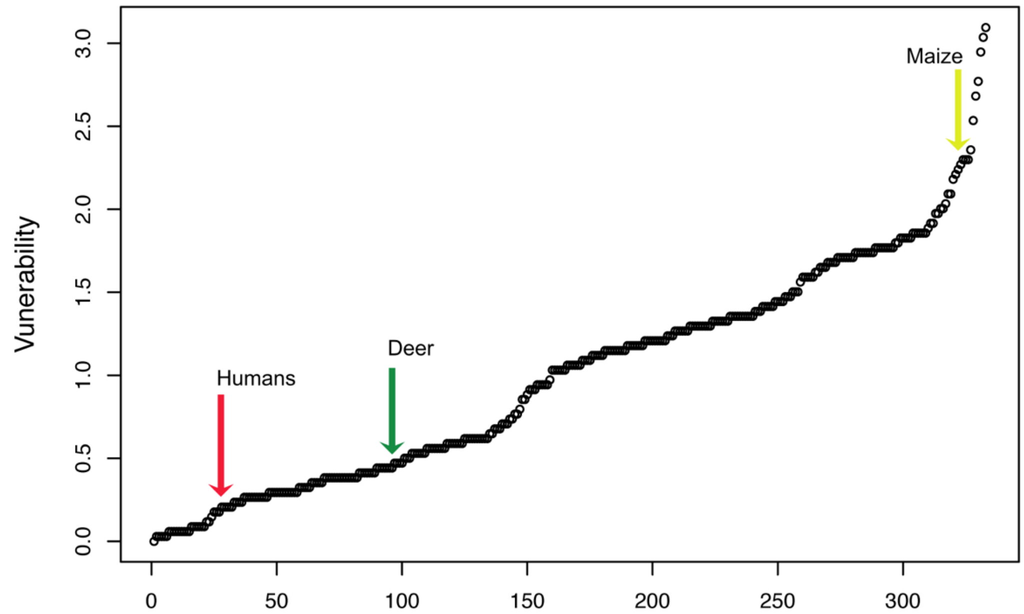


Figure 5.3. Vulnerability measures of species to predation; maize is the most vulnerable plant in our study area.

Trophic Level: Here, we use Williams and Martinez's (2004) estimates of trophic level (short-weighted trophic level). Typically, a trophic level of 1 is assigned to plants. A trophic level of 2 is generally herbivores, 3 omnivores, and 4 and above carnivores. Food webs display vertical organization (Figure 5.2), with node color corresponding to trophic level; red nodes represent primary producers (plants), orange nodes represent herbivores, yellow-orange nodes represent omnivores, and true yellow nodes represent carnivores. Vertices attenuate down the trophic level—they are thicker at the predator end and thinner at the prey end. Loops indicate cannibalism. Humans have a trophic level of 2.52, placing them at the 122nd highest trophic position out of 334 nodes. Carrion-eating animals and true carnivores are located at the highest trophic level. As evident in this figure, humans rank closer to herbivores than to carnivores—a fact that would be even more evident if the food web accounted for the abundance of maize in the diet.

Table 5.2. Scores for human trophic level, generality, vulnerability, connectivity and clustering coefficient by foodweb.

Trophic Web	Trophic Level	Generality	Vulnerability	Connectivity	Clustering Coefficient
Composite	2.521	3.710	0.265	1.987	0.103
Grass Mesa	2.468	2.233	0.264	1.249	0.117
Albert Porter	2.658	1.452	0.267	0.859	0.106
Sand Canyon	2.642	2.496	0.264	1.380	0.126

Table 5.3. Vulnerability and generality scores of primary prey for humans. White-tailed jackrabbit and snowshoe hare were not originally coded in the dataset, but were positively identified in an archaeological assemblage. Consequently, their vulnerability score only reflects being eaten by a few top species (humans, bobcat, cougars) and thus should not be taken as a true vulnerability score for these leporids.

Species	Vulnerability (# of predators)	Generality (# of prey)
Maize	2.27	n/a
Beans	1.21	n/a
Squash	1.21	n/a
Mule deer	0.47	3.39
Desert cottontail	1.15	0.41
Black-tailed jackrabbit	1.21	1.53
White-tailed jackrabbit	0.12*	1.68
Snowshoe hare	0.12*	1.68
Nuttall's cottontail	1.15	1.68

There are two main benefits for displaying data as in Figure 5.2. First, the density of links and quantity of nodes shows the high level of interconnection within the study area's ecosystem, taking discussions of environmental complexity from the abstract to the concrete. Second, as many food web studies also use the Networks 3D software (e.g. Dunne et al 2016; Williams 2010), displaying information this way allows for comparison among studies.

To focus on species most closely connected to humans, Figure 5.4 flattens the composite web and shows humans, human prey, and the prey of humans' primary prey (deer, turkeys, leporids). Here, line thickness shows the strength of interaction between humans and the other nodes, demonstrating the relative feeding strength for these species in human diet.

Clustering Coefficient: The clustering coefficient of a node measures how nodes within a given neighborhood are connected (Figure 5.5). The clustering coefficient can range from 0 to 1, with a value of 1 indicating that the node is completely connected to a clique (all nodes in a neighborhood are connected, i.e., each species preys on every other species in that neighborhood). A clustering coefficient close to 0 means that the focal node connects to other species, but those other species do not connect to one another. In Figure 5.6 species are sorted along the x-axis by clustering coefficients with the least-connected nodes near zero on both axes.

In the composite food web of southwestern Colorado the highest clustering coefficients correspond to bird and bat species—these species are in the most connected cliques (Supplementary Table 2). Humans, on the other hand, have a clustering coefficient value of 0.103, meaning that many of the species they prey upon do not prey on each other (Figure 5.6).

Connectivity: Connectivity measures how many other nodes a node is connected to. Here, the species with the highest connectivity are carrion eaters, such as the common raven (4.48) and the black-billed magpie (4.48), which will opportunistically eat almost all species, and which are eaten by many species as well (Figure 5.7). Humans are the 38^{th}-most connected species (1.99), though these links are mostly through consumption, not predation. Mule deer, with a connectivity value of 1.93, are the 40^{th}-most connected species in this analysis; they both consume and are preyed upon by many species.

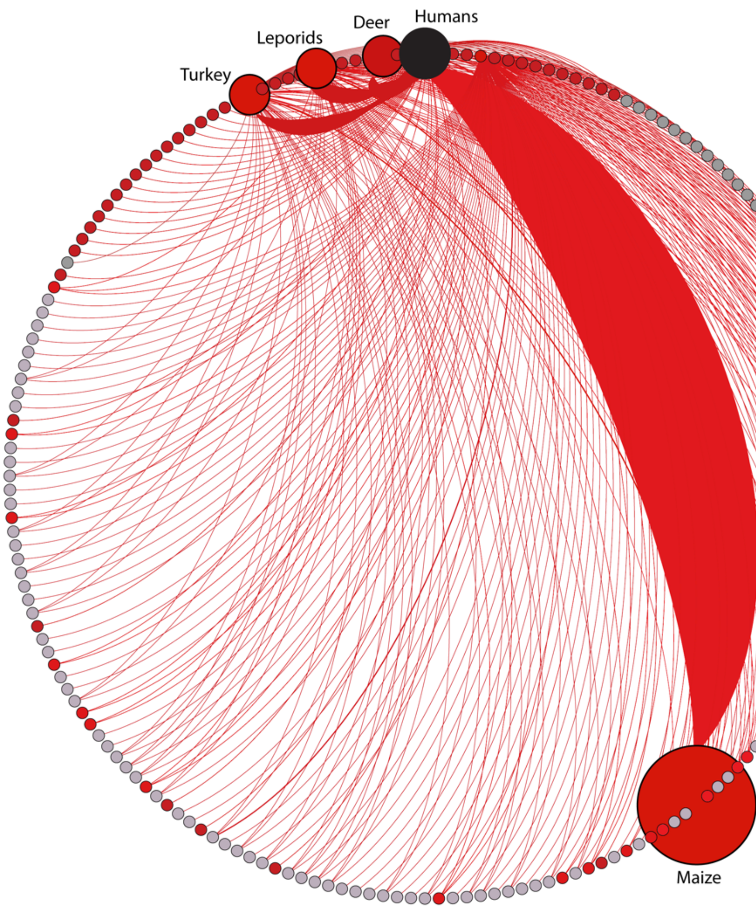


Figure 5.4. Primary prey of humans, leporids (cottontail and jackrabbit), deer and turkey taken from composite web. Red nodes are nodes that are connected to humans through predation. Size of node and thickness of edges approximates importance of species to consumer, with narrow edges being not important, and wide edges being very important. Maize makes up between 70 and 85 percent of diet. Deer, leporids and turkey each became important in human diet through Pueblo occupation. Primary prey of humans, leporids (cottontail and jackrabbit), deer and turkey taken from composite web. Red nodes are nodes that are connected to humans through predation. Size of node and thickness of edges approximates importance of species to humans. Maize makes up between 70 and 85 percent of diet. Deer, leporids and turkey each became important in human diet through Pueblo occupation.

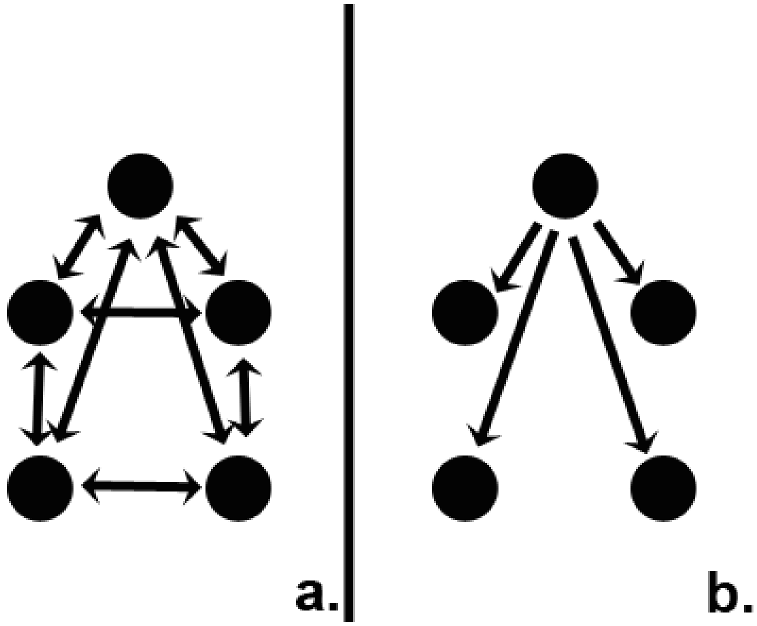


Figure 5.5. Ideal Clustering Coefficients. In (a) all species prey on each other, showing a complete connectance (or 1). In (b) only one predator preys on all other species, which do not prey on each other, showing a clustering coefficient close to 0.

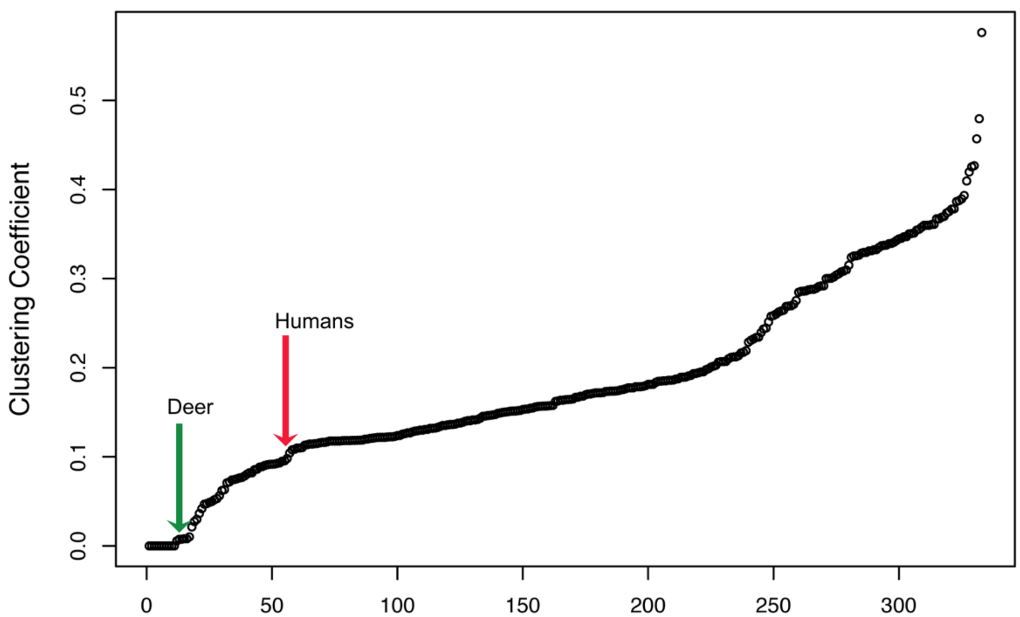


Figure 5.6. Clustering coefficient for the overall foodweb. Humans are mapped at point 51 on the x-axis, showing that humans are connected, but are well below the median species in this foodweb.

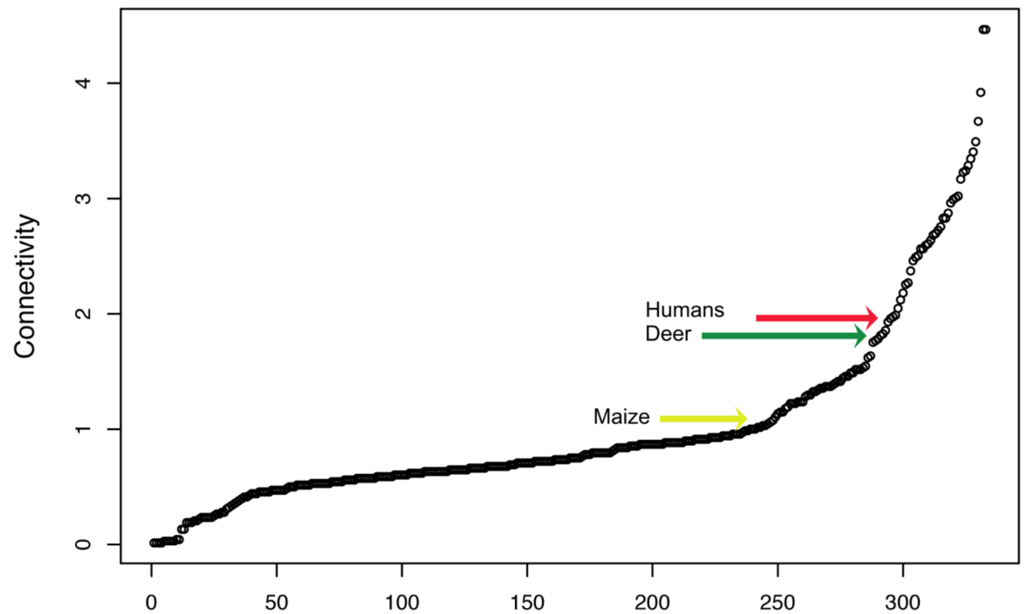


Figure 5.7. Connectivity measures. Here, humans are the 37th most connected species with a score of 1.987.

The Archaeological Food webs

We reconstructed trophic webs from three archaeological sites: Grass Mesa Pueblo (Figure 5.8) (Pueblo I; Neusius and Gould 1988; Matthews 1988), Albert Porter Pueblo (Figure 5.9) (Pueblo II; Adams 2015; Badenhorst and Driver 2015) and Sand Canyon Pueblo (Figure 5.10) (Pueblo III; Crow Canyon Archaeological Center 2004). Grass Mesa Pueblo was one of the largest villages excavated as part of the Dolores Archaeological Project (DAP). The methods developed for the DAP influenced those used by Crow Canyon Archaeological Center to excavate the Pueblo II and III sites discussed here. This minimizes any differences among these three assemblages due to sampling or analytical biases (see Methods).

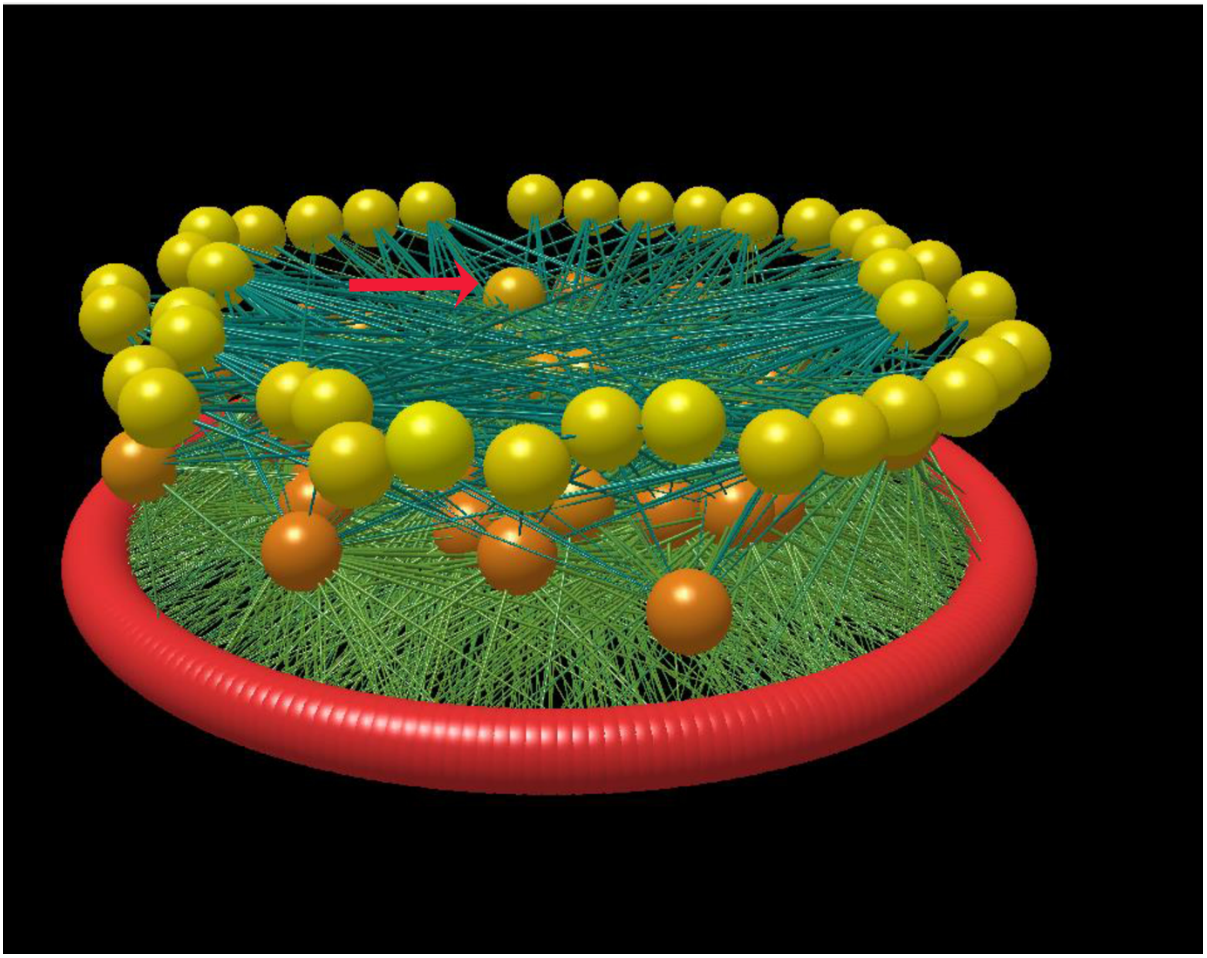


Figure 5.8. Human specific foodweb for Grass Mesa Pueblo, Pueblo I period. Arrow identifies humans.

The human-specific food web from the archaeological excavations at Grass Mesa Pueblo includes 314 nodes with 2,764 feeding links and an average number of links per species of 8.81, resulting in a much simpler trophic web than the composite web (Figure 5.8). In contrast, the human-specific food web for Albert Porter Pueblo is smaller, with only 249 species represented with 1,246 links among species, showing an average number of links per species of 5.01 (Figure 5.9). The Sand Canyon Pueblo's human-specific food web is the most connected human-specific web, with 321 nodes and 4,045 links among them, resulting in 12.63 links on average per node (Figure 5.10). Sand Canyon Pueblo was the largest site occupied of its time.

Trophic Level: The trophic level of humans is highest in the Albert Porter food web (2.658) and lowest in the Grass Mesa food web (2.468) (Table 5.2). While this study does not take into account the percent of the diet these organisms constitute, Ancestral Pueblo people did have a predominantly vegetarian diet (Matson and Chisholm 1991).

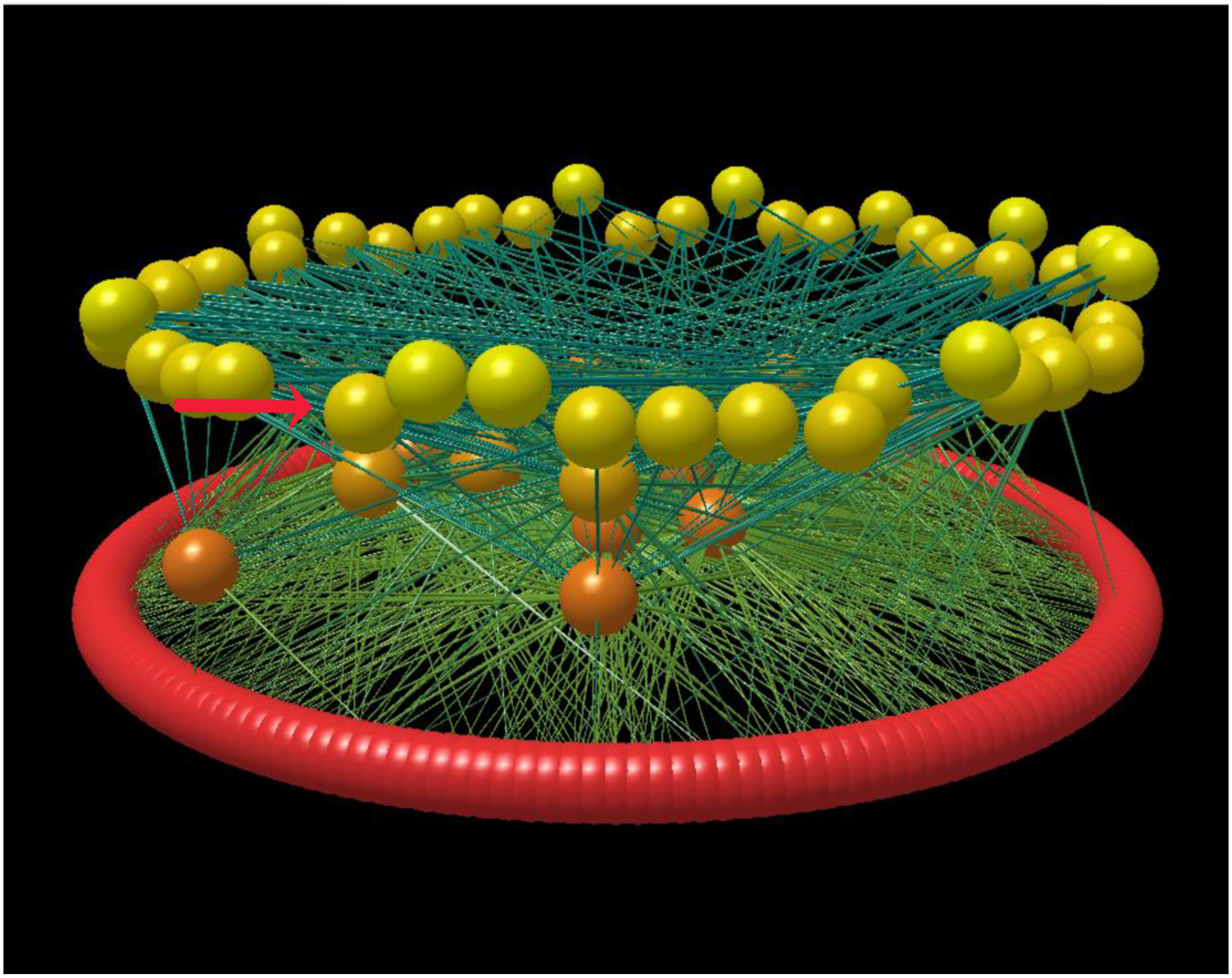


Figure 5.9. Human Specific Foodweb, Albert Porter Pueblo, Pueblo II period. Arrow identifies humans.

Clustering Coefficient: The clustering coefficients for the archaeological assemblages are all marginally higher than for the composite food web showing that humans and their prey are in slightly more connected cliques, with the highest clustering coefficient in the Sand Canyon Pueblo assemblage (Table 5.2).

Connectivity: As noted, connectivity shows how connected a species is to every other species. During Grass Mesa Pueblo occupation humans score 1.25 and are the 74th most connected species of 334 species. During Albert Porter Pueblo occupation, humans score 0.86 and are the 135th of 334 most connected species. During Sand Canyon Pueblo occupation humans score 1.38 and are the 60th most connected species. While humans are not the most connected species, they are still connected to many of the species on the environment.

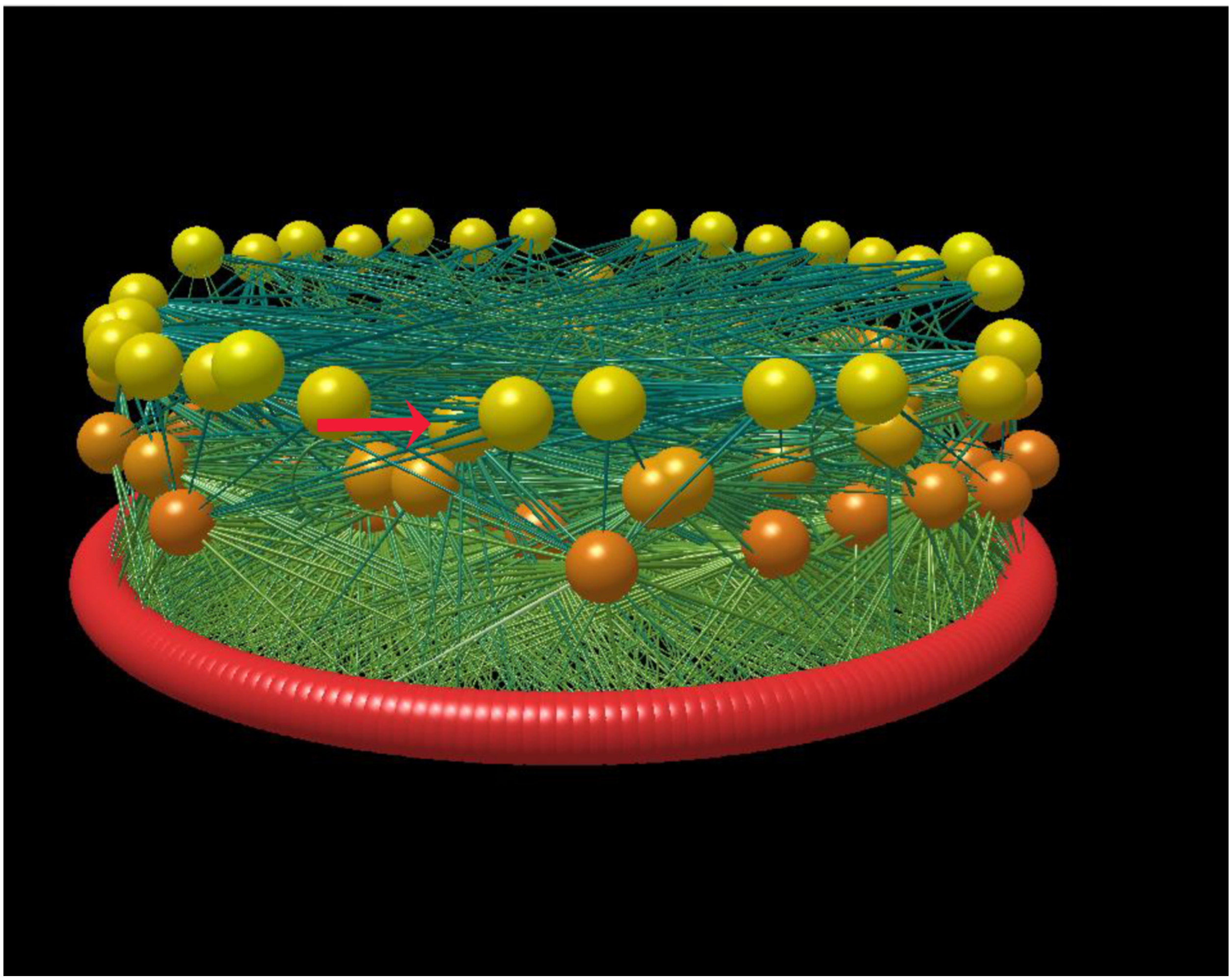


Figure 5.10. Human Specific Foodweb, Sand Canyon Pueblo, Pueblo III period. Arrow identifies humans.

Nodal knockout food webs

The above food web metrics do not take into account the strength of interactions between individual predator and prey nodes. However, we can examine the relative importance of nodes by performing a "nodal knockout" analysis and keeping only those species that are the most important to humans as prey in the constricted food webs. Species identified as most important by the nodal knockout analysis were corn, beans, squash, deer (before being hunted out), rabbit/hare, and turkey (after being introduced as a food source). Note that we did not remove those species that prey on humans, but simply replaced the matrix of human prey with these constricted assemblages.

Our first nodal-knockout analysis generated a constricted food web from Grass Mesa Pueblo including foods that were most common during Pueblo I occupation: maize, beans, squash, rabbits, hare and deer. While turkey are occasionally present in early assemblages, their use seems to be more for ritual than for food (Bocinsky and Kohler 2015). Humans' generality decreases in this web to 0.26, lower than in the complete Grass Mesa food web (Table 5.4). Second, the Albert Porter constricted food web from the Pueblo II period represents the period after deer were locally hunted out but before the introduction of domesticated turkey. In this constricted food web, humans' generality score decreases to 0.23 (Table 5.4). Finally, in the Sand Canyon constricted food web from the Pueblo III period we introduce turkey as a food source, and see the generality score raise to 0.26 again (Table 5.4). These nodal knockout results are important for identifying changes over time in humans' most important prey.

Table 5.4. Generality scores for both empirical data and the reduced foodweb, where only the most important species to Pueblo diet were included. These include corn, beans, squash, deer (before being hunted out), rabbit/hare and turkey (and after being introduced as a food source).

	Empirical	Reduced (Hypothetical)
Pueblo I (Grass Mesa)	2.23	0.26
Pueblo II (Albert Porter)	1.45	0.23
Pueblo III (Sand Canyon)	2.50	0.26

Discussion

To tie the food web findings to the broader archaeological context we discuss implications of the presence/absence data and network results in light of existing archaeological data. In particular, we examine evidence for human mediated environmental change and discuss how social choices can promote environmental degradation. These environmental changes and social adaptations create social-environmental feedbacks that led to the depopulation of the four corners area.

This study shows that both elk and showshoe hare were present during Pueblo I times, and completely absent in later assemblages. The National Resource Conservation Service lists lowland woodland cover as essential for winter survival and migration of both Rocky Mountain and Roosevelt elk (NRCS 1999). Elk also require high precipitation, and are thus found in higher elevations (Driver 2011). Similarly to elk, snowshoe hare require dense coniferous forests, bushy undergrowth, and high moisture (National Geographic 2015). If woody corridors become too patchy or woodland cover is clearcut, elk cannot successfully migrate to survive the winter and snowshoe hare would not be able to find proper forage or cover or reproduction (NRCS 1999; National Geographic 2015). Given comparable needs for woodland cover, the regional loss of both elk and snowshoe hare may have resulted from forest clearance during Pueblo I times

(Badenhorst and Driver 2009). If these species were hunted or forced out of the high elevations of Mesa Verde they may have become locally extinct, with forest disappearance preventing elk from migrating back into the area. While it is possible that these bones could have been transported into the area through long hunting forays or trade, their co-occurrence potentially suggests otherwise.

The disappearance of woodland-dependent species coupled with the arrival of species dependent on dry environments suggests severe environmental aridification and deforestation during Pueblo occupation. A recent study in *Science* (Morell 2015) shows that the feeding patterns of elk have detrimental effects on grass abundance; as long as there are high numbers of elk, grasslands suffer. The coincident disappearance of elk – which reduce grass abundance and depend on forested areas– and appearance of bird species – which depend on sparse grasslands and cannot live in dense woodland – suggests a large habitat shift in the Four Corners area, likely brought upon by centuries of clearcutting by maize farmers. With a natural environmental shift from moist in Pueblo I times to dry in Pueblo III times (Benson and Stein 2007; Bocinksy and Kohler 2014) and the concurrent clearcutting of forests for maize fields (Wykoff 1977), scaled quail and Sandhill crane thrived while elk and snowshoe hare suffered.

In the Rocky Mountains, 19th century pioneer journals rarely mention elk, suggesting that once their numbers became depressed it took centuries for them to rebound (Kay 1994; Kay 1995). Explanations for the depressed numbers of elk recorded in explorers' journals include a combination of "aboriginal overkill" (Kay 1994) and habitat loss through fire. Further south in Bandelier National Monument archaeological assemblages yield few elk remains (Allen 2004:56), though today elk are abundant. In the Four Corners, elk habitat disappeared during Pueblo occupation, and the recolonization of this species took centuries after the region was abandoned, coinciding with the disappearance of Sandhill crane and scaled quail.

The presence of Sandhill crane during the Pueblo period (but not during modern times) also suggests an environmental shift between A.D. 1300 and the present. Sandhill cranes require large expanses of grassland abutting standing water or marshland. Scaled quail also prefer sparse grasses and desert shrublands, and will not live in the thicker, woodier habitats of other quail and bobwhite species (Cornell Lab of Ornithology 2015). The rarity of Sandhill crane and scaled quail sightings during the modern period suggests that their habitat, open grasslands, became scarce. A recent mapping project displaying landcover (USGS Navajo Project 2016) suggests that much of the land separating the study region from Farmington, NM, the site of dense scaled quail populations, is currently forested, though this deserves more study.

In the face of changing environmental conditions and prey availability, human resilience is related to the ability of humans to be "versatilists" (Potts 1998), changing their prey choices to reflect current environmental and cultural conditions. Ancestral Pueblo people unintentionally decreased their versatility through practices related to their farming. Studies suggest that forests were clearcut during Ancestral Pueblo times in the Four Corners area. In the feature of Mummy Lake in Mesa Verde National Park, Wykoff (1977) found that only 15% of pollen from A.D. 1000-1225 was arboreal, a percentage that is so low as to suggest deforestation (Kohler 2004; Wykoff 1977). That same pollen core from Mummy Lake suggests rapid forest replacement following the depopulation of Central Mesa Verde, strongly pointing to humans as the agents of deforestation.

These pollen cores bolster findings that Pueblo farmers clearcut areas (through a combination of cutting, girdling, and burning) to make way for their farms (Kohler 2004; Wykoff

1977). Deforestation during Ancestral Pueblo times could have also led to soil erosion, depending on which type of vegetation (if any) replaced the trees (Kohler 2004:225), reducing the long-term ability of substrates to support vegetation. Further, pollen core studies also confirm that grassland dependent species could have benefited from deforestation during Pueblo occupation, while after Pueblo abandonment habitats shifted with the encroachment of pinyon-juniper forests. Our findings show that this woody encroachment coincided with the disappearance of Sandhill cranes and scaled quail from common bird species of the modern era; the window in which they existed in this region was only during Ancestral Pueblo occupation.

Generality and vulnerability scores from this study's network analysis are evidence for changes in the versatility of Ancestral Pueblo people. Low predation vulnerability scores are beneficial to the focal species, meaning few animals prey on that species. The opposite is true for generality—a low generality score means that that species preys on few animals. Low predation vulnerability and high generality scores characterize a robust species, while a less robust species would exhibit low generality and high predation vulnerability scores.

Humans have low predation vulnerability scores in all of the food webs, as they are preyed on by only large predators (e.g. wolves and cougars). In the composite and archaeological food webs humans have high generality scores, suggesting that they are generalists who may easily switch among prey, a finding well known in the anthropological literature (Staddon 1983). Note, however, that while the composite and archaeological webs document the presence and absence of species and feeding links, they do not take into account the relative importance of species to the diet (the strength of links). The nodal knockout analyses examine those species that were the most abundant in human diets. In the constricted food webs resulting from nodal knockouts, the generality scores of humans alternate between 0.26 and 0.23—both quite small—

indicating that humans would have had few options for error in this environment. Anthropologists have noted the health effects of a starch heavy diet (Mertz 1970:352) and the social effects of prey depression (Badenhorst and Driver 2009), which may both have been consequences when humans couldn't rely on a full suite of prey. In the nodal knockout analysis, humans have the 20th *lowest* generality score of all consumer species (non-plants).

The fact that humans have high generality scores if they can make use of the whole assemblage but low generality scores if they can only rely on the most important prey advances a line of reasoning that environmental pressures and human prey choice were intimately interconnected. We suggest that some families may have had access to preferred prey more easily than others, and so the generality score for the composite web may represent only those families that could readily prey switch, while the generality scores in the nodal knockout webs may in fact represent those families who faced constraints (e.g. population density) that limited their ability to prey switch.

Along with the generality score, the clustering coefficient is also related to human resilience. A high clustering coefficient indicates that the primary prey of humans also fed on each other, so the consumption of one organism may have cascading effects, either increasing or reducing the abundance of other prey species. Here we see that humans have a relatively low clustering coefficient across the composite and archaeological food webs. By consuming mostly species that are independent, cascading effects due to prey switching are limited. This strategy, intentional or unintentional, helps humans to minimize burdens they may otherwise place on themselves. The archaeological assemblages have a slight increase in mutual predation, most clearly in Sand Canyon Pueblo.

Another source of decreased robustness for humans can be seen in their trophic level. Energy is lost at every trophic level. The closer an organism is to the producer level, the more efficient that organism is in receiving energy from the basal trophic level (Yodzis and Inness 1992). In the above results we show that humans have a relatively low trophic level. By consuming low on the pyramid of biomass, humans are able to increase reproductive efficiencies (Kling 2015) while also accessing more biomass and calories. In contrast, consuming higher on the pyramid of biomass reduces reproductive efficiencies due to constraints of prey availability; the biomass that can be supported decreases by about 90% with each step up the trophic pyramid. The changing trophic level of Ancestral Pueblo people may indicate when times were good—during Pueblo II times they ate more meat—and when times were bad—during Pueblo III times they could not predictably eat the dense energy of meat.

The Albert Porter Pueblo assemblage represents fewer species than the other assemblages. If the size of the Albert Porter assemblage is a typical Pueblo II assemblage it indicates that Pueblo peoples relied on fewer prey during the Pueblo II period than in other time periods. Further south along the Salt and Gila rivers of Arizona, Dean (2007) showed that prior to the Hohokam collapse, increased diet breadth correlated with high demographic stress, while decreased diet breadth, seen in constricted assemblages, correlated with low demographic stress. The constricted assemblage in Albert Porter Pueblo suggests that Ancestral Pueblo people had low demographic stress and were able to rely on their preferred prey more easily than during other periods. Sand Canyon Pueblo, on the other hand, has the highest generality score. While this means that people living during Pueblo III times could prey-switch, the species richness may also suggest demographic stress and the inability for humans to rely on their preferred food sources. Toward the end of the occupation of Sand Canyon Pueblo, archaeologists find that humans were unable to rely on domesticated crops due to drought and thus switched to a wild foods diet (Kuckelman 2010). An increase in diversity, such as at Sand Canyon Pueblo, means that at the assemblage level people relied on undesirable species. However, we stress *at the assemblage level* because there were likely many strategies for each family in each archaeological site—some families may have met their needs through preferred prey, while others could not. Higher populations have greater effects on the overall environment making it difficult to switch from cultivated foods. In light of the nodal knockout analysis, which show low generality when humans rely on their preferred foods, we can see how detrimental a reduction of species would be for the Ancestral Pueblos. If soil fertility decreased following deforestation, these small increases in mutual predation and trophic level may have had important effects on the susceptibility of Ancestral Pueblos to environmental shifts.

Conclusions

The environmental footprint of the 27,000 inhabitants of the study area (Schwindt et al. 2016) would have included forest clearing to find beams for houses and woody fuels for fires, and to clear land for maize gardens. In addition to this, the ability to relocate, or even rotate fields, would be curtailed by density—where once there were large enough tracts of arable land to enable fallowing of nutrient poor soils, people would instead be forced to innovate new ways to maintain their fields. The inability to move because of human density coupled with the environmental effects *of* human density (erosion, nitrogen poor soils, traveling far for woody fuels, scarce or absent prey species) would have gradually decreased the quality of life of Ancestral Pueblo people. And while it is true that during some times humans could switch prey to other native species ("starvation foods" as Kohler et al. (2008) call them) this choice was only available for all people when human density was low.

While it is easy to discuss deforestation, species shifts, and prey depression in the abstract, ecological changes would have been felt differently by different people in the Ancestral Pueblo world. Decisions were likely made at the individual, family, village and clan levels. While *in the aggregate* humans may have been resilient to environmental shifts, aggregate conditions would not have applied to individual families who experienced starvation. The individual effects of ecological changes would have been dramatic and devastating for many Pueblo farmers. The high populations resulting from the Neolithic demographic transition forced humans into a rigidity trap, enabling overall survival only through high agricultural production. Once turkeys were introduced, maize farming became even more critical, and the ability to use other weedy species decreased (Bocinsky and Kohler 2015). If the soil became too poor to support maize fields due to centuries of human use, the Ancestral Pueblo people needed to prey switch to survive. In such circumstances, if previously available forage had become scarce (elk, snowshoe hare, the forests that supported them) the people would have been forced with a difficult decision: starve, develop social responses to starvation (e.g. violence), or migrate.

People along the margins of the Central Mesa Verde region likely felt climatic changes first (Schwindt et al 2016). These farmers were unable to sustain rain-fed agriculture in the face of a shrinking maize-growing niche (Bocinsky and Kohler 2014). Those farmers on the margins may have been the first to attempt to utilize the suite of foodstuffs available to them via prey switching. This would only be available in the short term, however. As human settlement density increased and forests were cleared, and as humans decreased fallowing periods for their fields (increasing erosion) the effects of environmental changes would be felt more strongly. This would lead to *further* social adaptations--trades with neighbors, raiding those you don't know--which may in turn increase other types of social pressures (paying back donated gifts, building defenses against invaders). If the environment did not bounce back quickly--which here we suggest it did not--the environmental and social pressures may have become unbearable, especially for those families that colonized marginal lands. Due to the density and extent of human habitation and years of environmental degradation decreasing native flora and fauna, farmers on the margins were likely the first to decide to migrate away from the Central Mesa Verde.

Future Food webs studies

The research we present here is part of an increasing body of studies using food webs to evaluate human/ecosystem interactions. The detailed analysis of archaeological cultures and the ecosystems in which they lived provide a means to examine human reactions to changing environments worldwide.

Dunne et al. (2016) have placed humans in trophic webs from western Alaska. Creating dynamic models of food webs, they show that Aleuts were "super generalists," feeding on many species in the region. The researchers in this project (Dunne et al. 2016; Maschner et al 2009) suggest that humans are important managers of ecosystems who promote ecological integrity. This research also further shows the necessity of including humans to gain a full understanding of ecosystem structure and dynamics.

Recent research in French Polynesia examines the sustainability of humans in island ecosystems of the South Pacific (Martinez et al 2013-2017). This research seeks to understand the trajectory of human/environment interaction, using those methods developed by Dunne et al (2016). While this project is ongoing, it is promising a third well-developed case study to compare human-environment interactions in the same manner as applied both in the research presented here, and that presented by Dunne et al (2016).

The research we presented in this paper provides a terrestrial case study that can be directly compared with the island systems studied by Dunne et al (2016) and Martinez et al (2013-2017). Our results show how important a nuanced understanding of a culture and its environment is to truly understand the challenges that culture faced. Even agricultural groups are intimately connected with their environments, and to understand environments we need to understand how humans structure them. Further, small acts may have unintended consequences that benefit some species (such as scaled quail benefiting from decreased forests) while simultaneously hurting other species (such as elk or snowshoe hare). These domino effects can only be understood through large-scale analyses, using the 'big data' of food web matrices, and only through studying the unique contingencies that these cultures faced may we begin to understand patterns of human/environment interaction, social adaptation, and the effects of species addition and removal. The increasing body of knowledge we have on food webs shows the importance of humans in structuring ecosystems: how we dramatically alter ecosystems, and how we can manage ecosystems to prevent potential species loss. By comparing these well-developed cases we can better understand our place in the global ecosystem.

Acknowledgements

This research was made possible by grant DEB-0816400 and was conducted while supported by NSF Graduate Research Fellowship DGE-080667, the NSF GROW fellowship and the Chateaubriand Fellowship. An earlier version of this research won the American Association for the Advancement of Science 2012 poster competition, social sciences division. Several researchers have contributed to the success of this research. This research was first presented at the Santa Fe Institute Complex System Summer School in 2011; feedback from Jennifer Dunne, David Krakauer and Cormac McCarthy advanced this research. Thanks to the Sao Paolo School of Ecological Networks and Thomas Lewinsohn for feedback on the next steps. Great thanks for feedback on earlier manuscripts by Kathryn Harris, Laura Ellyson, Andrew Duff, Tim Kohler, Kyle Bocinsky and Mindy Wilkinson. S. Crabtree developed the study, performed analyses, compiled matrixes, performed background research and helped design study methodology; any problems with the paper are strictly hers. N. Crabtree helped compile matrixes and perform research on species in the Four Corners area. Vaughn helped design study methodology and assisted in writing.

CHAPTER 6: CONCLUSIONS

Societies in prehistory consistently faced issues related to depletion of critical resources and uncertainty due to climatic variability. Two complementary approaches exist for examining these issues. The inferential, historical approach has long been our main ally. This dissertation, however, applies a deductive, modeling approach to understanding the archaeological record, augmenting traditional archaeological studies.

I began this dissertation suggesting that archaeologists implicitly desire to study human relationships, but that the study of material culture does not lend itself to studying how humans interacted in the past. The tools and theories I employed from a complex adaptive systems approach, however, provided a way to understand human interaction in the past. Through the use of agent-based modeling and trophic network analysis I was able to analyze the interactions of individuals, groups, and species.

Of paramount importance to this dissertation is the idea that individual decisions matter—an idea taken from a complex adaptive systems approach. The approaches used here demonstrate how the decisions of individuals can lead to rapid, societal change, and it is through the computational approaches of agent-based modeling and network analysis that we can more readily understand these changes.

In chapter three I introduced the simplest model in this dissertation. In that model Gaulish agents farmed grain and traded grain-surplus for wine grown by Etruscan and Greek merchant agents. I suggested that the social hierarchy that was already in place in Gaul when trading merchants arrived was reinforced by the consumption of a luxury product—wine. I showed how the actions of individuals (growing agricultural products, trading those products) can have large effects on the system (the survival of one group at the expense of another) and that we need to understand the interactions of individuals to understand the trajectory of Gaulish society.

The decisions of individuals led to the proliferation of one type of wine over another in the case study presented in chapter three. In the archaeological record we can see the presence of different types of amphorae, but we cannot see how they were traded or why they were bought; this agent-based model enables a further nuanced understanding of the decision-making processes of Iron Age Gauls, colonist-merchants, and their resultant interactions.

In chapter four I created a second agent-based model, this one with more complexity than that presented in chapter three. In this model, which we call "Polity," agents are households that form groups and play a public goods game within their group. Groups of agents come into conflict over arable land, and hierarchical groups of groups form, which we term "complex groups." I demonstrated that the distribution of simulated complex-group sizes followed a power-law distribution during Pueblo II times, with the distribution weakening toward a log-normal distribution during Pueblo III times. By comparing the distribution of group sizes in the simulation output against distributions of kiva-membership sizes and the sizes of momentized household populations within sites I suggested that the trend toward power-law distributions during Pueblo II demonstrated the consolidation of power of groups at the top of the hierarchy. This consolidation of power, I suggested, weakened during Pueblo III times, away from one paramount group and toward localized power, at the site (community) or group-of-sites (communities) level. The model enabled the analysis of group-level properties—in the article presented therein, group hierarchy. While the archaeological analyses shed new light on the social structure of groups in the Ancestral Pueblo Southwest, it was only through the comparison with the agent-based model that the plausibility of the development of a multi-tiered hierarchy could be determined. This study further reinforced the utility of agent-based modeling in examining complex processes that could not be clearly understood from the archaeological record alone.

In chapter five the discussion moved from the individual household to the aggregate of the species. However, the analyses presented therein demonstrate how decisions by Ancestral Pueblo people, of which species to hunt and of where to plant their fields, would have had dramatic ramifications for species richness on the landscape. While the immediate effects might only be felt locally, the analyses presented in chapter five show that enough of these local decisions can dramatically alter environments, making them inhospitable for certain species (such as snowshoe hare and elk) and eventually eradicating them altogether. These changes, I suggest, led to increased vulnerability of Ancestral Pueblo people and made those living on the margins more susceptible to environmental fluctuations.

Through the application of complex systems theory, the utilization of tools commonly used in complexity science, and careful comparison of simulated output to archaeological data, we can delve deeper into an understanding of what forces drove societies in the past, and better understand the lessons they have for us today.

Lessons from these studies

There are two types of lessons from these studies: those that forge new methodological approaches for archaeology, and those that suggest an understanding of humanity in both prehistory and today.

Methodological advances

These three studies show the utility of complex adaptive systems approaches for studying the archaeological record. I approached two long-standing questions via agent-based modeling. First, the question as to how the curves of artifact percentages (from Etruscan to Greek amphorae) identified by Py (1990) formed in southern France. While this was a highly simplified model, it enabled an analysis of Gauls as drivers of the Iron Age economy of Littoral France, and solidified an understanding that choice likely propelled the transition from Etruscan to Greek amphorae. Pure economics could not explain the complete replacement of Greek amphorae by Etruscan amphorae. Only Gaulish preference for one type of wine over another led to the curves of artifacts seen in the archaeological record.

Second, I approached the century-long debate as to the hierarchical nature of Ancestral Pueblo people via an agent-based modeling approach. I showed that through a simple process of territorial expansion, large village-spanning polities could form in the prehispanic American Southwest.

These two models demonstrate that simulations built with a keen understanding of the system being modeled can provide insights that traditional archaeological analyses cannot. This is not to say that my models were the first to propose the mechanisms; Dietler (2010) and Py (1990) both suggested Gauls as economic drivers, and Lekson (2015) and some others have been proponents of a pan-regional hierarchy centered around Chaco Canyon. Rather, the models I presented allowed for the examination of these ideas suggested from other researchers, and it is only due to the decades (almost centuries) of archaeological research that I was even able to build an agent-based model based upon sound historical data.

Agent-based modeling provides a way to see the actions and interactions of individuals (or families/households) that are difficult to reconstruct with traditional archaeological methods.

While agent-based modeling is still changing, models have increasingly been able to include diverse strategies and viewpoints, including one unique agent-based model (built by an archaeologist) attempting to model the sense of smell (Rocks-McQueen 2015).

The food webs case study presented in chapter five also utilizes a tool from complex adaptive systems—network analysis—to understand cascading effects of prey choice and ecosystem shifts in the southwest. This paper demonstrates how simple actions can have dramatic unintended consequences. Large tracts of arable land were cleared in the Southwest to make way for maize, changing the ecosystem in ways that may still be felt today. While food web studies have been used for decades, long before the advanced computational tools we see today, the approach used here enables a true modeling of interactions of every species, helping to understand not just the complexity of the ecosystem of the central Mesa Verde (it was certainly complex!) but also the nuanced ways the ecosystem shifted through time.

Understanding the trajectory of humanity

Archaeology assists in understanding our trajectory as a species by providing a long-term view of the relationship between demography, distribution of human group sizes, environmental factors, exchange, and violent conflict. Perhaps it is easiest to see the lessons for humanity from chapter five. This study shows how small decisions can have multiplicative effects on our ecosystems. Humans create their own niches to live, but often this niche creation can be at the expense of other organisms. When those organisms disappear (as did elk and snowshoe hare) this not only signals an ecosystem shift, but also changes the structure of the foodweb. When the foodweb structure changes dramatically this will alter the way that humans interact within their own ecosystems. I suggest in chapter five that human resilience can be seen by the decision to migrate away from the central Mesa Verde and begin new strategies elsewhere. This luxury can only be afforded when populations are relatively sparse. When density increases, we have to learn to adapt in the ecosystems that we have changed. The study suggests that we need a nuanced understanding of our environments worldwide to know how we are affecting our global ecosystems.

The study in chapter four also suggests that increased density can have dramatic effects on sociopolitical evolution. While in chapter five population density decreased the availability of species, in chapter four density increased the likelihood that groups would become part of a large polity. Our study suggests that the development of polities elsewhere in prehistory may have followed a similar trajectory—with expansion into the available arable lands, and the subsumption of smaller by larger groups. Examining the extent to which alliances form out of conflict, or as a means of providing positive per capita return in procurement of resources, may help to predict breaking points in alliances in other systems worldwide. As our population grows today we must not only understand the ecosystems we are changing, but also the way our social structures change, to avoid the types of violent conflicts that plagued the Ancestral Pueblo people.

While chapter three paints a rosier picture (of economic gains) it may have lessons for the growth of populations with the influx of non-local migrants. In Iron Age Gaul the Gauls and the visiting merchants became entwined in complex economic partnerships. Understanding how native groups interacted in the past both within their groups, with their environment, and with immigrating colonists has important implications today. Worldwide there are currently 51 million refugees (Sengupta 2014), more than any time since World War II (Hadid and Krauss 2014), causing governments to search for solutions for how to interact with large populations of immigrating individuals from different cultural groups. Understanding how native and immigrating societies coexisted in the past can be helpful for creating peaceable solutions. By studying the economic and social networks that develop among different cultural groups in Southern France, the archaeological record may be able to help inform policy for how to create productive interactions between native and immigrating populations.

Future researchers will be able to build on these three models to understand the complex dynamics of human relations in other societies. We are poised at a cross-roads as a civilization, plagued by many of the same issues that our ancestors faced. An understanding of our past can help us make informed decisions about our future.

Supplementary Text for Chapter Three: ODD protocol: Simulating Littoral Trade: Modeling the trade of wine in the Bronze to Iron Age transition in Southern France

By Stefani A. Crabtree

1. Purpose

This model explores a simple economic model, examining the transition from one type of artifact to another. In this simulation one type of artifact holds a monopoly in an area until a new type of artifact appears; the transition between these two is examined through an economic model of strictly local processes. This is done through an archaeological case study of southern Gaul. While this model examines economics (the shift from a monopoly object to another object) it also intervenes in long-standing debates about the prehistory of France. One of the main purposes of this model is to create the first agent-based model in French archaeology. As such, this model uses simplified landscapes and simplified agents to examine trade in prehistory. This model will eventually expand from basic principles to a richer representation of real-world scenarios.

2. Entities, state variables, and scales

State Variables: Two State Variables were parameterized in this simulation. The first is Grain Trade Rate, and the second is Preference.

Grain Trade Rate: Grain trade rate examines the quantity of grain in hectoliters traded for 10 amphorae of wine. This is set at the system level. While future models may enable barter, the model presented here sought to reduce variables, so a state-level rate was used. In this simulation the optimum trade rate was 40 hectoliters of grain for 10 amphorae of wine. This is explored in section 2.1 of the manuscript.

Preference: preference refers to which type of wine a Gaulish agent will choose to purchase. Gaulish agents choose a random number between 1 and 100, and compare that number to their preference value (Table 1). If the Gaulish merchant chooses a number that favors Etruscan trade, they will preferentially trade with Etruscans. If the Gaulish agent chooses a number that favors Greek trade, they will trade with Greeks. This value was set at the simulation level, so simulations were run with one preference value per run. This was examined in section 2.1 in the paper, and is described further below under Scheduling: Buying Wine.

Table S.3.1. Preference Values swept across in this study.

Preference	Explanation
0	Weight is strongly in favor of Etruscan Wine
10	Weight is strongly in favor of Etruscan Wine
20	Weight is in favor of Etruscan Wine
30	Weight is slightly in favor of Etruscan Wine

40	Weight is slightly in favor of Etruscan Wine
50	There is no weighted preference between Greek or Etruscan wine.
60	Weight is slightly in favor of Greek wine.
70	Weight is slightly in favor of Greek wine.
80	Weight is in favor of Greek wine.
90	Weight is strongly in favor of Greek wine.
100	Weight is strongly in favor of Greek wine.

Agents/individuals. In this model agents represent the economic production unit of a household. There are two types of agents—Gaulish agents, and Merchant agents.

Gaulish agents: Gaulish agents are farmers. They extract grain from the land, and the amount they extract depends on the size of their household. The size of the household corresponds to the amount of grain they have in storage, which is seen in Table S.3.2 below.

Merchant agents: Merchant agents make wine and must trade wine for grain, since grain is essential for survival. The size of merchant households also scales with the amount of grain they have stored, although they need more grain to increase their household size than Gauls do. This is due to the inability of merchants to grow grain; they must plan more to be able to raise daughter households. There are additionally two sub-types of Merchant Agents:

a. Etruscan Agents: Etruscan agents arrive at timestep 34 (see below) and bring Etruscan wine.

b. Greek Agents: Greek agents arrive at timestep 100 (see below) and bring Greek wine.

Table S.3.2. How storage level affects the number of individuals in a household and their consumption rates. This enables agents to increase their family size, and thus the productivity of their land, as well as increasing the ability to trade. However, once an agent trades, its storage level will be cut in half (as half is donated to the daughter household) decreasing the household size in the process. Merchants have a higher storage level because they cannot grow their own food, and thus need to plan more to be able to raise daughter households.

Storage Level Merchants	Storage Level Gauls	Size of plots Gauls	Size of harvest Gauls	Consumption Rates Gauls and Merchants	Corresponding number of individuals per household
< 45 *hl*	<= 10 *hl*	5 *ha*	40 *hl*	6 *hl*	1
>= 46, <50*hl*	>10, <=30 *hl*	5 x 1.5 (7.5 *ha*)	60 *hl*	12 *hl*	2
>=50, <60*hl*	>=31, <=40 *hl*	5 x 2 (10 *ha*)	80 *hl*	16 *hl*	3
>=61, <70*hl*	>=41, <= 50 *hl*	5 x 2.5 (12.5 *ha*)	100 *hl*	20 *hl*	4
>=71*hl*	>=51 *hl*	5 x 3 (15 *ha*)	120 *hl*	24 *hl*	5

- *Spatial units (e.g., grid cells)*. The simulation window is divided into three types of grid cells: water, littoral cells, and land cells. One time step represents one year and simulations were run for 500 years. One cell represents 5 hectares, and the model landscape comprises 80 cells by 80 cells, i.e. 32,000 hectares.

    - *Water*: These cells take 2400 cells (12,000 *ha*) to the southern end of the simulation window. Water cells currently are not used in the simulation, and are kept for aesthetic purposes and for future development. For example, the littoral zone of France was one of the biggest producers of *garum* (Roman fish sauce) in the antique world, so future models may take advantage of sea resource exploitation.

    - *Littoral cells*: These cells take 320 cells (1600 *ha*) that abut the water cells. Wine can only be grown along the littoral zone. Cells here correspond to viticultural areas. Cells are not affected by changes in productivity, since modern wine farms are long lasting.

    - *Land cells*: These cells take 3680 cells (18,400 *ha*) in the rest of the simulation window. These cells correspond to grain farms. Cells have a 5-year lifecycle before they are unproductive and must be laid fallow for up to 5 years to be cultivated again.

3. Process overview and scheduling

Gaulish agents farm grain, while merchant-agents trade wine for grain. Below, the scheduling for both of these agent types is described.

Gaulish Scheduling: 150 Gaulish agents are placed randomly on the land portion of the landscape and given 20 grain on outset. When each year begins Gauls follow the following processes in this order: reproduction, planting grain, harvesting grain, eating grain, storing any extra grain, buying wine (if merchants have arrived), moving to a new patch (if the patch is unproductive), consuming any wine they bought, and finally checking their storage to see if they die. Each of these is explained below.

Reproduction: Reproduction is via fission and follows that established in the "Wolf-Sheep Predation" model developed by Wilensky (2005). Each year agents assess their stored calories. If their calories are above a threshold that enables a division of calories between parent and daughter offspring equal to or greater than one year's metabolic needs, they probabilistically reproduce. For this simulation, agents were given a 3% probability of reproduction at every timestep as long as their storage is above the reproduction threshold.

When an agent reproduces it divides its storage evenly between itself and its offspring. Offspring spawn to a patch near their parent's patch, preferably one cell away, but if all those cells are occupied, to a random cell within their required cell-type (merchants in the littoral zone, farming Gauls on vacant green patches). Agents are not allowed to live on sea-patches.

Planting: Gauls can only plant on a productive patch and are charged 4 grain units (hectoliters) to plant. Gauls would have needed to store seed to plant their fields each year, and planting would be energetically costly. Thus the parameter "planting" encapsulates both the stored grain, and the cost to plant a large field.

Of note, when fields are planted, a "degredation clock" is set on the cell. Each cell can only be planted for five years before it needs to lay fallow for between 1 and 5 years.

Harvest: When Gaulish agents harvest grain they harvest the quantity according to the number of individuals in their household, which is determined by the amount of storage they have accrued (Table S.3.2). Harvest, however, is costly, and the costs are fixed (they do not scale like harvest amount does). The amount can be encapsulated by the following formula:

$H_t = H_a - H_c$

Where H_a equals the amount harvested, calculated from Table 1, H_c equals the costs of harvesting, H_t equals the total harvested.

Harvests are known to come in at once and need to be harvested rapidly before the grain falls off the stalk. Thus Gauls likely relied on others to help with harvest who needed provisioning to help with the harvest. Further, some grain that grew may be lost in harvest, due to improper techniques, harvesting too late, or storing improperly. Thus "harvest" encapsulates the costs associated with harvest and storage. In the sweep presented here H_c is 4*hl*.

Eating grain: Eating grain is encapsulated in "consumption rates" in Table 1. The amount of grain eaten scales according to the number of individuals in a household. When individuals eat grain it is taken from the storage first; if storage is not sufficient, the calories are taken from the recent harvest (which is stored in the next step).

Storing grain: Here Gaulish agents store the grain that is leftover from the harvest, or H_t.

Buying wine: When Gaulish agents have a storage of twice the Grain Trade Rate (described above) they assess a probability, in this simulation set to 1%, of whether or not they will buy wine in the current year. If they will buy, who they buy from depends on what year it is in the simulation.

After Etruscan Arrival, before Greek Arrival: In this case, Gaulish agents ask an Etruscan agent if it has enough wine to sell. If it does, Gaulish agents trade the amount of grain set by Grain Trade Rate for 10 amphorae of wine. The Gaulish agent then calculates the distance between itself and the Etruscan agent. It multiplies that number by a carrying-cost multiplier (set to 0.25 for the simulation), and subtracts that quantity from storage. So,

$$D_{ge} * 0.25 = GTC$$

Where D_{ge} is the distance between the Gaulish and Etruscan agents, 0.25 is the carrying-cost multiplier, and GTC is the amount to be subtracted from Gaulish storage. This distance factors into how Gaulish agents choose to move.

After Greek Arrival: If Greek Merchants have already arrived, Gaulish agents assess their preference for which type of wine they like best. This is in Table 2. Gaulish agents choose a random number between 1 and 100, and compare that number to their preference value (Table 1). If the Gaulish merchant chooses a number that favors Etruscan trade, they will preferentially trade with Etruscans. If the Gaulish agent chooses a number that favors Greek trade, they will trade with Greeks. Then the Gaulish agent follows the same protocol as above, calculating its distance and subtracting carrying costs from its storage.

Consuming wine: Wine is consumed at one amphora per type, per year, and is decreased from the Gaulish amphorae storage.

Moving to a new patch: In this model cells degrade after 5 years of farming use; cells become productive again after up to 5 years lying fallow, set randomly. If a Gaulish agent's farm cell has become unproductive, the agent must move to another cell. When Gauls move, they will look at its most recent trading costs and assess how costly they were. If the trading costs were greater than ¼ of the grain in storage, the agent will move to a productive cell closer to the merchant settlements. If the costs were less than ¼ of the agent's grain storage, the agent will simply look for another productive cell in a radius of 10 cells to begin a new farm. The Gaulish agent is charged 1 *hl* to move to a new farm.

Death: If an agent has a total of 0 grain in its storage (or if it has 0 grain in both storage and its immediate harvest total) an agent dies. Further, if an agent has reached its life expectancy (set to 80 for this simulation) the agent has a 5% probability of dying each time it calls the "death" function.

Merchant scheduling: 50 Merchant agents of each type are placed on the littoral portion of the landscape and given 60 grain on outset. When each year begins Merchants follow the following processes in the order presented below.

Trade wine: The first thing merchant agents do is try to trade wine, since this enables them to get grain. If a Merchant agent has less than 20 *hl* of grain, it rolls the dice and has a 25% chance of attempting to buy grain. The Merchant agent asks a Gaulish agent with twice the Grain Trade Rate in storage to sell. The Merchant agent then calculates the distance between itself and the Gaulish agent. It multiplies that number by a carrying-cost multiplier (set to 0.25 for the simulation), and subtracts that quantity from storage. So,

$D_{gm} * 0.25 = GTC$

Where D_{ge} is the distance between the Gaulish and Merchant agents, 0.25 is the carrying-cost multiplier, and *GTC* is the amount to be subtracted from Merchant storage.

Reproduce: Merchants then reproduce. Reproduction is via fission and follows that established in the "Wolf-Sheep Predation" model developed by Wilensky (2005). Merchants assess their stored calories. If their calories are above a threshold that enables a division of calories between parent and daughter offspring equal to or greater than one year's metabolic needs, they probabilistically reproduce. For this simulation, agents were given a 3% probability of reproduction at every timestep as long as their storage is above the reproduction threshold.

When an agent reproduces it divides its storage evenly between itself and its offspring. Offspring spawn to a patch near their parent's patch, preferably one cell away, but if all those cells are occupied, to a random cell within their required cell-type (merchants in the littoral zone, farming Gauls on vacant green patches). Agents are not allowed to live on sea-patches.

Consume wine: Wine is consumed at one amphora per type, per year, and is decreased from the Merchant amphorae storage.

Eat grain: Eating grain is encapsulated in "consumption rates" in Table 2. The amount of grain eaten scales according to the number of individuals in a household. When individuals eat grain it is taken from the storage first; if storage is not sufficient, the calories are taken from the recent harvest (which is stored in the next step).

Plant/tend vineyard: Vineyards only are planted once, but are costly to maintain. Merchants are charged 4 grain units (hectoliters) to plant and maintain their vineyards. Merchants would have needed to prune branches, check for molds and diseases, and maintain the soil of their vineyards.

Harvest wine: Harvesting grapes and turning them into wine would be costly. The cost of harvest was set to 4*hl* for this simulation, while the yield was set to 10 amphorae of wine for this simulation.

Grapes ripen at once and need to be harvested before they rot, are eaten by scavengers, or freeze on the vine. Thus Etruscans and Greeks likely relied on others who needed provisioning to help with harvest. Further, some grapes that grew may be lost in harvest, due to improper techniques, harvesting too late, or storing improperly. Thus "harvest" encapsulates the costs associated with harvest and storage. In the sweep presented here H_c is 4*hl*.

Death: Death follows the same as it does for Gauls. If an agent has a total of 0 grain in its storage (or if it has 0 grain in both storage and its immediate harvest total) an agent dies. Further, if an agent has reached its life expectancy (set to 80 for this simulation) the agent has a 5% probability of dying each time it calls the "death" function.

System scheduling:

Each year, at the beginning of the year the simulation checks to see if there are no agents, or if there have been more than 500 years since the start of the simulation. If either of these are true, the simulation stops.

After Gauls, then Etruscans, then Greeks perform their scheduling as detailed above, the simulation checks its carrying capacity. Then the simulation regenerates dead patches, and finally degrades those patches that need degrading.

Carrying capacity: This catch is rarely used in the simulation. A carrying capacity of 1000 Gauls, 600 Etruscans and 600 Greeks was set for the simulation. If there are greater than that many agents for each type, all agents that are above the life expectancy (set to 80) die that year. Otherwise, as described above, those agents that reach the carrying capacity have a 5% chance of dying every year. This ensures that the simulation is not overpopulated with very old agents.

Regrow patches: Once a cell has been farmed for five years it needs to lay fallow before it can be refarmed. Each cell is given a random number between 0 and that set by the parameter "grass regrowth time" and has that many years to regrow. It is updated yearly until the patch is productive again.

Degrade patches: When a patch is occupied by a Gaulish agent and farmed it is given a 5-year clock. Each year this is updated, until it has been 5 years, when the cell starts its "regrow patches" clock.

4. Design concepts

Questions: There are eleven design concepts. Most of these were discussed extensively by Railsback (2001) and Grimm and Railsback (2005; Chapter. 5), and are summarized here via the following questions:

Basic principles Existing models for the interaction between Gaulish inhabitants and colonial traders along the littoral (the region abutting the Mediterranean) of southern France are descriptive. According to Py (2012:135) the paradigms underlying research by proto-historians working in these contexts can be summarized as follows: indigenous Gauls living along the littoral zone were forced to abandon some of their traditional practices, such as semi-nomadic pastoralism, to generate the agricultural surplus required to develop their economies and engage in trade with outsiders (Py 2012). Yet these descriptive models have not been formally tested; thus, the research here formally examines how early colonialism can create distinctive economic partnerships and artifact patterns. This model examines these principles, formalizes them, and explores them. First I assess whether it would have been feasible for Etruscan and Greek merchants to live in Southern France if they did not farm—could Gauls have provisioned them? Second, I examine whether the replacement of Etruscan amphorae by Greek amphorae could be generated by strictly local processes. This is the first model made in Southern France, so it is highly simplified, with the goal of adding realism after this model is published.

Emergence. The emergent property in this model is the distribution of artifact types across the landscape. As this model has variable productivity related to the use of the landscape, costs associated with trading, and the reality that Gaulish agents do not need to trade for wine to survive, the decisions of Gaulish agents on where to farm, when to reproduce, and when to trade will effect Merchant survival. Gauls also decide to move based upon the costs of trading, so this will effect where they plant. Since Merchants can initiate trade, and Merchants need to trade to survive, their "goals" are potentially at odds with Gaulish agent goals. Even though Gauls prefer one type of wine over another, since Merchants can initiate trade as well, they *should* be able to survive. However, this simulation shows that there are phase transitions related to preference after which it's hard for one or another type of Merchant agent to survive. This shows the emergence of the replacement of one artifact type over another.

Adaptation. Gaulish agents only trade when they have above a certain threshold of stored grain. This will dramatically affect the survivability of Merchant agents. Gaulish agents "want" to survive and reproduce. Wine helps decrease harvest costs, but buying wine decreases storage. Therefore a Gaulish agent must "choose" each timestep to reproduce and/or to trade. They adapt by moving their farms to reflect the costs that trading incurred.

Objectives. Objectives for agents are to maximize storage, maximize reproduction, and minimize harvesting costs. These are accomplished by farming, storing, reproducing, and buying wine (for Gauls), or harvesting, trading, and reproducing (for Merchants).

Prediction. Merchant agents predict future consequences of having too few grain and seek to trade with a Gaulish agent. If they have too few grain they die. Gaulish agents predict the costs related to trading based on previous costs, and attempt to minimize those in the future.

Sensing. Gauls can "sense" when their homecell is no longer productive, and choose to move to a productive cell. This is tied to how much it cost to trade for wine the last time they traded.

Interaction. The direct interaction modeled in this simulation is trade, and trade is only between Gaulish agents and Merchant agents. Indirect interaction is between Etruscan and Greek agents. Since both of them have to live along the littoral cells, they compete for arable land. If one population is higher than the other, it becomes increasingly hard for the other agents to live on the landscape.

Stochasticity. Preference is partly random; Gaulish agents choose a random number between 1 and 100 and compare that to the preference value, which drives whether they trade with one type of agent or another (Table 1). It is improbable, but possible, that even with a high preference value (90—in favor with Greeks) that every Gaulish agent could choose an integer of the remaining 10 and always trade with Etruscans. Further, reproduction is random, as agents only have a 3% chance of reproducing at every timestep. Finally, a random subset of cells at the onset of the simulation are set to be unproductive, and that determines where Gaulish agents can initially farm.

Collectives. Collectives are important in this simulation, as they dictate who trades with whom. Gauls are a collective, Etruscans are a collective, and Greeks are a collective.

Observation. Both individual level and population level statistics are collected from this simulation. Individual level statistics include the amount of Etruscan or Greek wine an agent has, and the amount of storage an agent has. Group level data include the population of each agent type through time.

5. Initialization

Simulation Instantiation: At simulation instantiation, the different types of patches (described above) are created. 1/3 of all land patches are unproductive on the first year of the simulation, and each of these patches are given a random regrowth clock (set to 60 timesteps initially) to allow them to become productive for farming. The region Gauls entered had been used by semi-nomadic forager-farmers for centuries, so it is reasonable to expect that not all of the land was available for farming upon their arrival, either due to being occupied by other groups, due to over exploitation, or due to thick vegetation that needed clearing. The simulation will look slightly different on initialization every time due to the random placement of unproductive patches, and the random placement of Gauls. When Etruscans, and later Greeks, arrive they are placed randomly along the littoral.

6. Input data

No input data was used for this version of the simulation.

7. Submodels

In this model, the user can choose to have one type of merchant agent (default set to Etruscans) or two types of merchant agents (Etruscans and Greeks). These were analyzed separately in sections 2.1 and 2.2. These are two submodels—first examining the ability for merchant agents to survive when they do not farm, and second examining the competition between two types of Merchant agents.

While this was not examined here, infrastructure is in place to allow for two types of Gaulish agents—those that farm exclusively, and those that mine for metals that can then be traded. This resource diversification model is another submodel, which will allow the examination of different types of goods that were traded to visiting merchants.

This model will be made available publicly on Open ABM upon publication of this paper.

Supplemental Figure S.1. Composition of landscape in the model zoomed in on littoral zone, with distribution of agents on the landscape. This screenshot was taken after both Greek and Etruscan agents have landed on the landscape. The south is denoted by the sea, and bright green littoral patches that abut the sea. Merchant populations live in littoral; blue = Etruscans, orange = Greeks. While three orange shapes are in the sea, that is because they are newborn agents; they spawn to a cell near their parents, and then move if they accidentally spawned on the sea. The rest of the simulation window is earth patches where farming Gauls can live. Brown denotes farms, red person shapes denotes Gauls.

Supplemental Text for Chapter Four

Detecting Outliers in Kiva Size Distributions

The power-law analysis package works best on large datasets reporting populations rather than samples. Unavoidably, our data represent a convenience sample. This leads to some strange distributions, as is evident in the All-PIII kiva data, as well as the NSJ PII and PIII kiva data. Clauset (personal communication 6/10/2016) suggests that these results (in which the "compare distribution" and "test statistic" indicate power-law distributions despite power-law probabilities of 0) likely reflect some of the oddities of our sample, which probably includes over-sampling of larger kivas from the population.

To remedy this we attempted to identify outliers, here defined as those kivas that were more than 1.5 midspreads in size from the upper bound on a boxplot (Drennan 2009:39). This markedly improves the fit of the NSJ and All-PIII kiva-size distributions to a power law distribution (Supplemental Table 3). This same technique does not need to be applied to our other datasets, which are either populations (as in the case of the simulation territory sizes) or, in the case of our site sizes, are in most cases derived from block or transect surveys in which all recognized sites were recorded.

Taking this additional analysis into account does not affect our agreement with Clauset's assessment (personal communication 6/10/2016) that the NSJ PII, NSJ PIII and All-PIII datasets correspond weakly to power-law distributions.

Model: The Public Goods Game

To the household/ecosystem dynamics represented in the base version of "Village" we added (in Kohler et al. 2012, and retained here) the concept of social groups defined as sets of households playing an annually repeated public goods game among themselves. A set of households that internally plays an annual public goods game is called a simple group. The exact nature of the public good in question is left unspecified in the model; the costs and benefits in the game are denominated solely in maize. In the Pueblo world, plausible examples of public goods include defense (Rusch 2014) or construction of public resources such as reservoirs (Wilshusen et al. 1997) and great kivas, and perhaps great houses themselves.

Households within a simple group may choose to work under a leader who can greatly reduce the likelihood of failures in cooperation due to free-riding or lack of coordination among households in the group. As in any public goods game, if every household contributes to the public good, the return to each is higher than its contribution. Yet there is a temptation to defect, since the reduction in returns to defecting households is generally less than the costs of contributing to the public good. If some agents choose to defect (not contribute), the returns to all households decrease. In the Kohler et al. (2012) model, leaders ensure that defection is punished, and when the cost of supporting a leader is less than the losses incurred by defection, groups who choose to support a leader prosper. The model is evolutionary, so that strategies yielding higher returns slowly replace less-rewarding strategies. Whereas simple groups may be either hierarchical, or non-hierarchical, a robust result of the model is that as group size grows to the point where "mutual monitoring" for defectors becomes too costly, households in groups submit to the greater costs, but even greater benefits, of supporting a leader, thus becoming hierarchical.

Model: Parameter Selection, Group Formation and Territoriality

In a further extension of this model we made these social groups territorial and allow them to subsume other groups by warfare, creating hierarchies of groups that we called "complex groups" (Kohler et al. in review). The model presented below differs from that in two main ways, both related to fission: first, once groups are subsumed by dominant groups, they may attempt to remove themselves from the hierarchy (revolt); second, when group population reaches its maximal group size (parameterized in Table 3) the group divides in two. While many parameters could be varied, in the model presented here we were concerned specifically with how maximum basal group size, fatalities from warfare and parameters surrounding tribute affect the growth of complex groups. Consequently the parameters we varied reflected these goals (Table 3). *S* indexes the proportion of fatalities among all its combatants the smaller group is willing to suffer before conceding defeat; β is the proportion of a subordinate group's net benefit from the public goods game paid to its direct dominant as tribute; and μ is the proportion of that tribute passed through an intermediate group to a dominant group (1--μ therefore being the tax kept on that pass--through). We explored all combinations of unique values for these four parameters resulting in 2 x 2 x 3 x 3 = 36 combinations, each of which was run 15 times for a total of 540 runs, allowing us to recognize variability within and between parameter combinations.

In the model discussed here, groups maintain territories that grow as group membership grows and new members colonize new farmland. Group territories are calculated by drawing the smallest possible polygon around all agents within each group. If group territories come in contact hindering further expansion, groups may choose to engage in violent conflict. The concepts of groups, public goods games, territoriality, merging, warfare, and tribute are central to this model. We describe them below but for more detail please see Kohler et al. (in review).

All agents are able to act in ways that are appropriate to either a hierarchical or a non-hierarchical setting, as described in Kohler et al. (in review:Table 1). Agents track their ancestry to one of 200 foundational households and express hierarchical or non-hierarchical behaviors based on majority preference within each simple group. While in Kohler et al. (2012) groups were formed by agents who wanted to live in groups that were similar with respect to their preference for living in a hierarchical vs. non-hierarchical group, in the model reported here (and in Kohler et al. [in review]) groups are composed of kin who may have similar preferences relative to hierarchy due to inheritance. Hierarchical preferences may still change through time given a slow evolutionary dynamic in which agents in groups making the higher-return choice out-reproduce those in groups making the lower-return choice, and a faster social learning dynamic in which agents emulate the hierarchical preference of the household with the most storage in its neighborhood (which may include some households in other groups).

Model: Conflict, Merging, and Tribute

Agents require arable land to produce maize to provide their basic caloric intake. New households (formed by marriage) may not be able to locate productive fields within their group's territory, or established households may need to add plots if production is declining or the kids keep arriving. New households must seek new locations, and expanding households may as well if adding plots locally is not possible. In seeking new locations agents keep track of "frustrations" which occur any time they cannot move to a cell because that cell is already fully occupied, in another group's territory, or because such a move would cause the territories of their group and another group to overlap. In low-population settings (typically within the first 300 years of beginning the simulation) an appropriate unoccupied cell, not in another group's territory, can often be found within the allowed search radius.

If however an agent needs to move and all the more productive cells are in another group's territory or claiming the cell would cause the two group territories to overlap, that is termed a "frustration that hurts." A group with a household needing to expand into another group's territory (because no other options are available) will choose to confront one of the groups on its periphery that is causing a "frustration that hurts." Groups maintain a list of the groups with which each of its households has frustrations. Each year the group sorts this list according to both the distance between the two groups and the number of frustrations it has catalogued. The focal group iterates through its frustrations list, calculating its likelihood of winning a battle against each by comparing the attrition thresholds (*s*) of each group (the probability that the smaller group will reach its attrition threshold sooner than the larger group) which depends (with some stochasticity) on the relative number of fighters in each group. Generally larger groups are willing to confront smaller groups.

When this happens, the focal group first tenders an offer of merger, which, if accepted, will subsume the frustrating group as a subordinate, creating a "complex group." (We discuss the implications of merging below.) The group offered a merger likewise calculates its likelihood of winning in a fight against this opponent; with some stochasticity, if it is smaller, it will likely not win, and therefore accepts the merger. If the frustrating group declines the offer to merge (because its probability of winning is favorable), the groups may fight. Assuming that fighting does not result in a stand-off, the winning group subsumes the loser. Our use of stochastic Lanchester's Laws in making these decisions is explained in algorithmic detail in Kohler et al. (in review).

If conflict occurs, groups calculate the number of casualties they would expect in a conflict. Ancient warfare was generally less lethal than modern warfare, with fighting ending once a group suffered a relatively small quantity of casualties, often around two percent of its fighters (Keeley 1996:91). In the simulation here we set a parameter of attrition, which we call *s* (Table 3), at values of 0.02 and 0.05 of the smaller number of fighters as the acceptable quantity of casualties in a battle.

Ability to levy tribute is a defining characteristic of power in complex societies (Steponaitis 1981). Once groups are in a hierarchical relationship subordinate groups pay tribute to their dominant group, which here is calculated as a tax on the net benefit of each subordinate's public goods game. The proportion of that benefit rendered as tribute is the β parameter in Table 3. If there are more than two groups in a chain then each subservient group pays a tribute in this proportion to its directly dominant group. Groups with a dominant that receive these flows from a subordinate pass along this tribute, retaining (1 - μ) of it for the favor. Since β and μ index proportions of the net benefit to the public goods game, a dominant group might receive no tribute, especially if a subordinate group is non-hierarchical. Even in that case, however, another benefit of hierarchy is defense. When a group is attacked, or attacks another group, that group calls on its direct dominant and all subordinates for assistance. Dominant groups receive the benefit of tribute from their subordinates (if the public goods game is successful) in addition to the benefit of defense. The model we present here makes two main changes to that described by Kohler et al. (in review), one giving simple groups the possibility of revolting from polities, and the second allowing simple groups that grow too large to split in two (fission).

Model: Revolt in Complex Groups

In Kohler et al. (in review) we did not allow for simple groups to leave a complex group, despite abundant ethnographic and archaeological evidence that doing so is common (e.g., Flannery and Marcus 2012:170; Turchin and Gavrilets 2009). In the previous model, if the group on top of the complex hierarchy became small in population it would still receive tribute from its subordinate groups who had no mechanism to protest. In the model reported here, simple groups may decide whether to attempt to secede (revolt) from the complex group.

Every year after they play the public goods game, subservient groups assess whether they should try to revolt, using the same algorithms as for merging/fighting, considering each group's number of fighters (males from 15 to 50 years old). Revolts are undertaken if the odds of success (in terms of the number of fighters on each side) appear favorable. The group considering whether to revolt considers both its own fighters and those in each of its subordinate groups if any, since it will take those subordinates along if its revolt is successful.

Some of the dynamics in complex group formation are illustrated in Supplemental Figure 8. Even with the change in fissioning noted above, it can still happen that smaller groups dominate larger. In the case where a dominant group has more than one chain of subordinates, those from one chain will be enlisted to help suppress a revolt from members of the other, so that polities with chains branching just below the top are most invulnerable to revolt (Supplemental Figure 8, panel 6).

Model: Fission of Simple Groups

In our earlier work on this model, when a simple group reached its maximum group size, individual households would bud-off to form their own groups. This process is meant to reflect the fact that simple groups, even those with leaders able to induce cooperation in a public goods game, eventually reach size thresholds such as "Dunbar's number" (2008) beyond which growth is difficult. The previous process however created many groups of size 1 that would often become immediately subordinated to the nearest larger group.

In the model version reported here, when groups reach 50 or 100 agents (Table 2), they will fission into two groups of approximately equal size, with new groups dictated by propinquity. We employ a k-means clustering algorithm to divide the group into 2 polygons. This algorithm creates 2 candidate centroids at random and associates each household in the group with the nearest centroid. New centroids are then calculated for each group and new assignments are made, and so forth in an iterative process terminating when group assignments no longer change.

On fission the smaller group loses its subordinate groups, but keeps its dominant group. The larger of the two groups keeps its subordinate groups as well as its dominant group. Fission is therefore costly to the group that leaves.

Supplemental Tables for Chapter Four

Supplemental Table 1. Kiva sample sizes in each subregion by period. One kiva in the MSJ, seven in the CCP, and 33 in the NSJ were counted as spanning the PII and PIII periods.

	PII (~890-1145)	PIII (~1145-1285)
Northern San Juan	162	151
Middle San Juan	37	25
Chaco Canyon	128	10

Supplemental Table 2. Simulation parameters by run number. Each parameter combination was run 15 times.

Run Number	Maximal Group Size	*s*	BETA	μ
1	50	0.02	0.1	0.1
2	50	0.02	0.1	0.5
3	50	0.02	0.1	0.9
4	50	0.02	0.5	0.1
5	50	0.02	0.5	0.5
6	50	0.02	0.5	0.9
7	50	0.02	0.9	0.1
8	50	0.02	0.9	0.5
9	50	0.02	0.9	0.9
10	50	0.05	0.1	0.1
11	50	0.05	0.1	0.5
12	50	0.05	0.1	0.9
13	50	0.05	0.5	0.1
14	50	0.05	0.5	0.5

15	50	0.05	0.5	0.9
16	50	0.05	0.9	0.1
17	50	0.05	0.9	0.5
18	50	0.05	0.9	0.9
19	100	0.02	0.1	0.1
20	100	0.02	0.1	0.5
21	100	0.02	0.1	0.9
22	100	0.02	0.5	0.1
23	100	0.02	0.5	0.5
24	100	0.02	0.5	0.9
25	100	0.02	0.9	0.1
26	100	0.02	0.9	0.5
27	100	0.02	0.9	0.9
28	100	0.05	0.1	0.1
29	100	0.05	0.1	0.5
30	100	0.05	0.1	0.9
31	100	0.05	0.5	0.1
32	100	0.05	0.5	0.5
33	100	0.05	0.5	0.9
34	100	0.05	0.9	0.1
35	100	0.05	0.9	0.5
36	100	0.05	0.9	0.9

Supplemental Table 3. Power-law probability values for distributions after removing outliers above 1.5 midspreads above the upper bound.

Area/Period	Power-law probability	Compare distributions	Test statistic	Outlier threshold
All PIII	0.18	1	5.65	48
NSJ PII	0.8	0.96	1.75	40
NSJ PIII	0.18	1	5.35	50

Supplemental Figures for Chapter Four

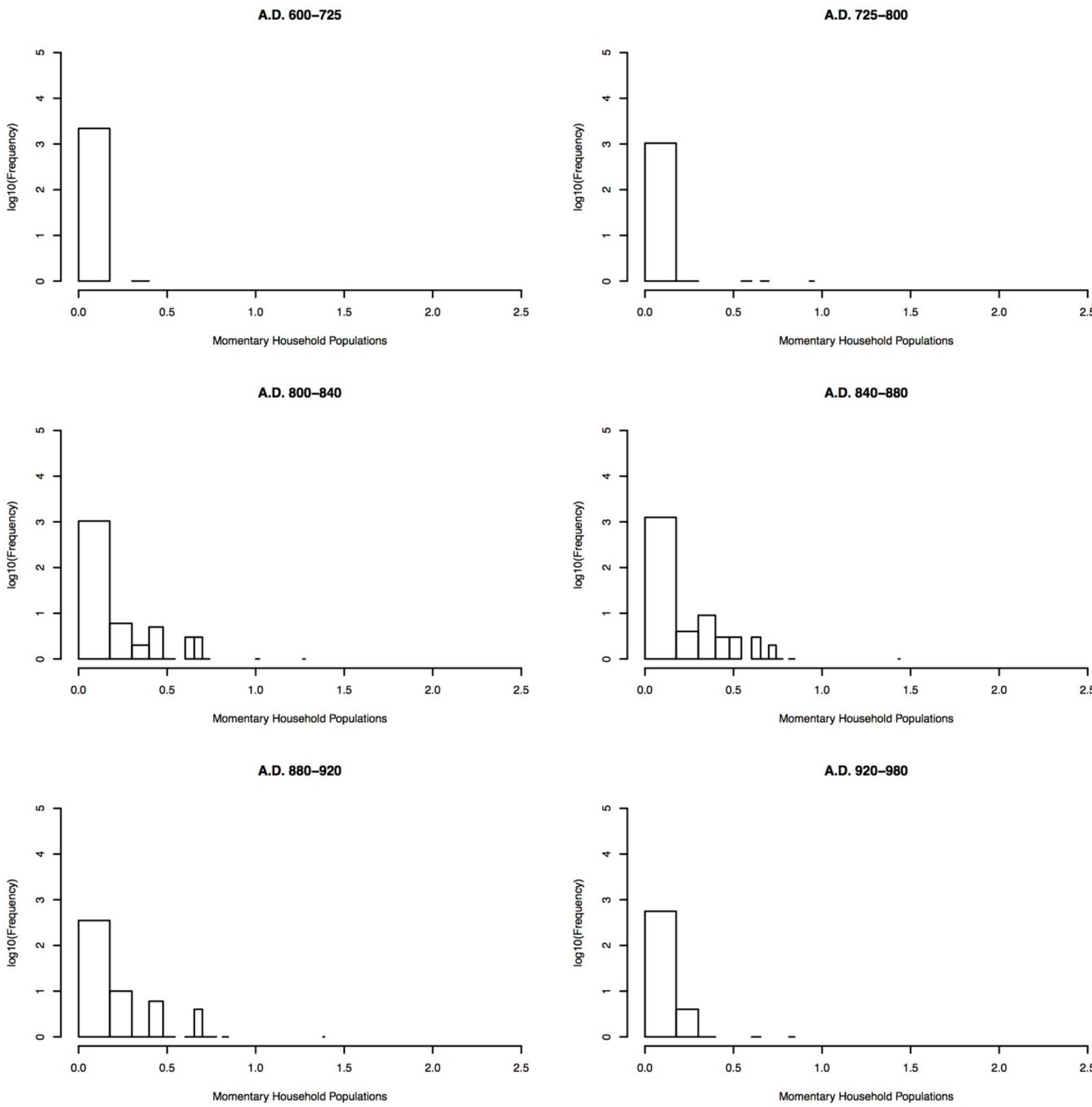


Figure S.4.0.1. BMIII-PI momentary households by number of settlements in VEPIIN study area. Both axes logged.

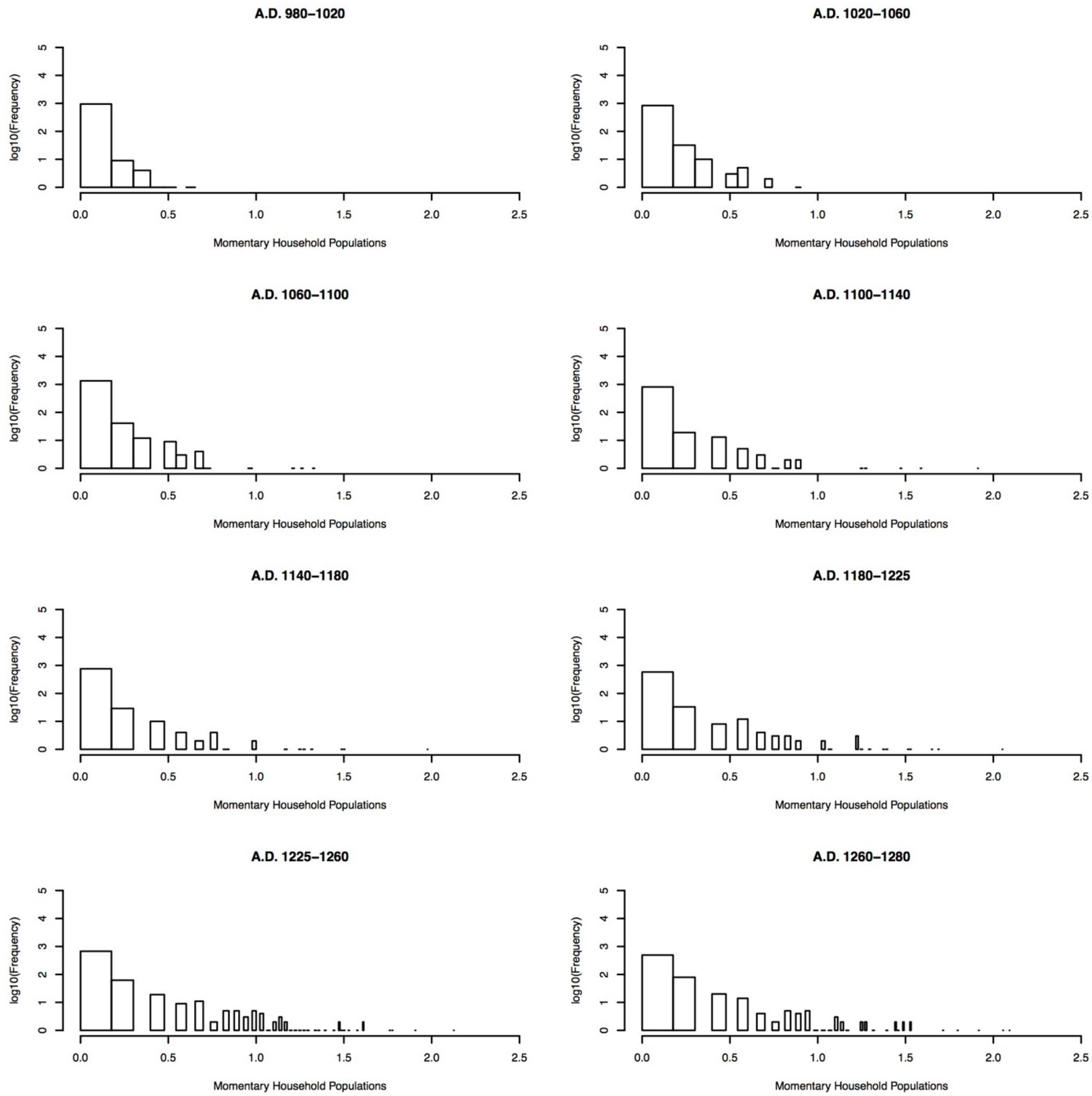


Figure S.4.0.2. PII-PIII momentary households by number of settlements in VEPIIN study area. Both axes logged.

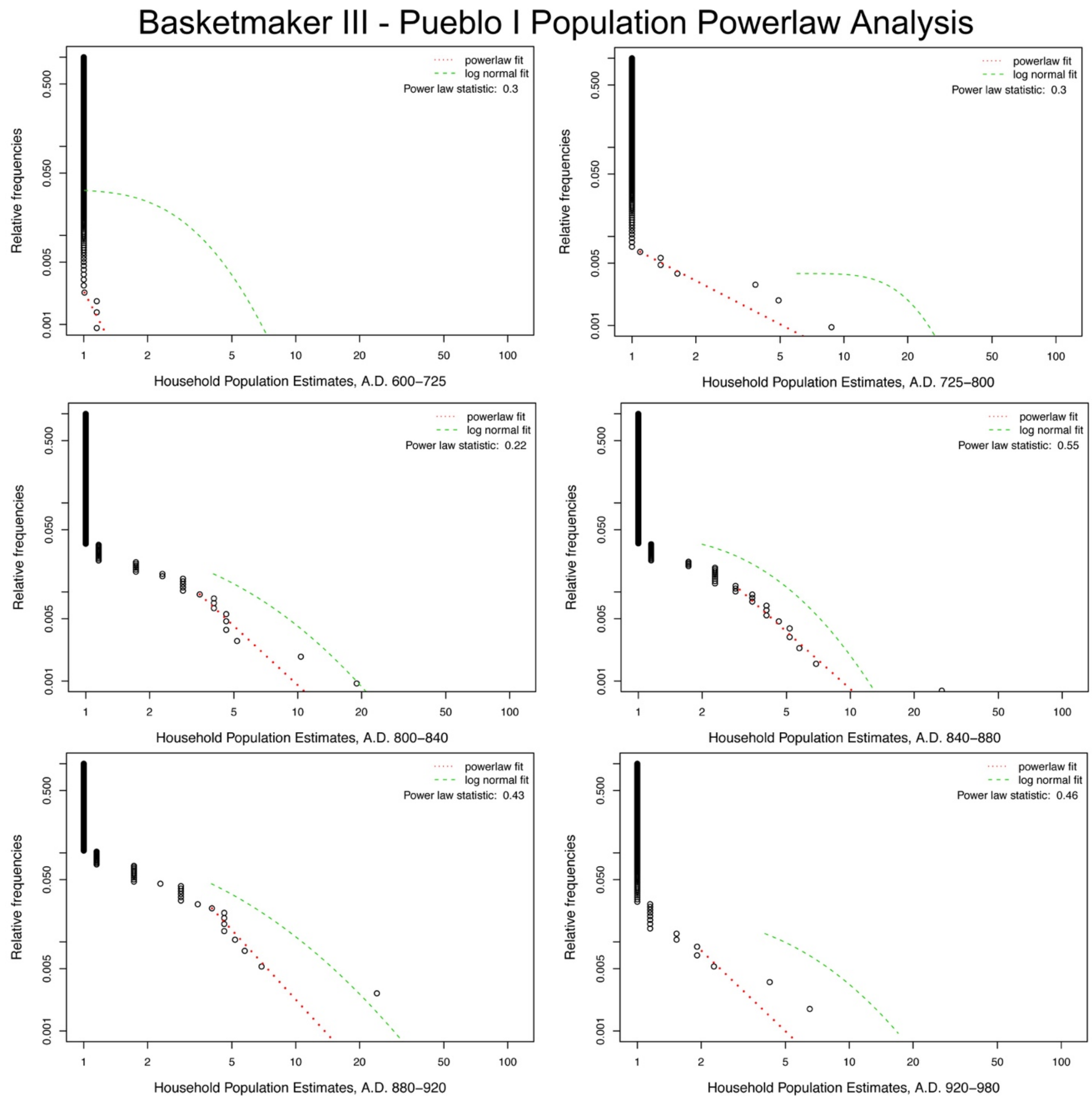


Figure S.4.0.3. Power-law analysis of BMIII to PI Momentary Households in the VEPIIN study area.

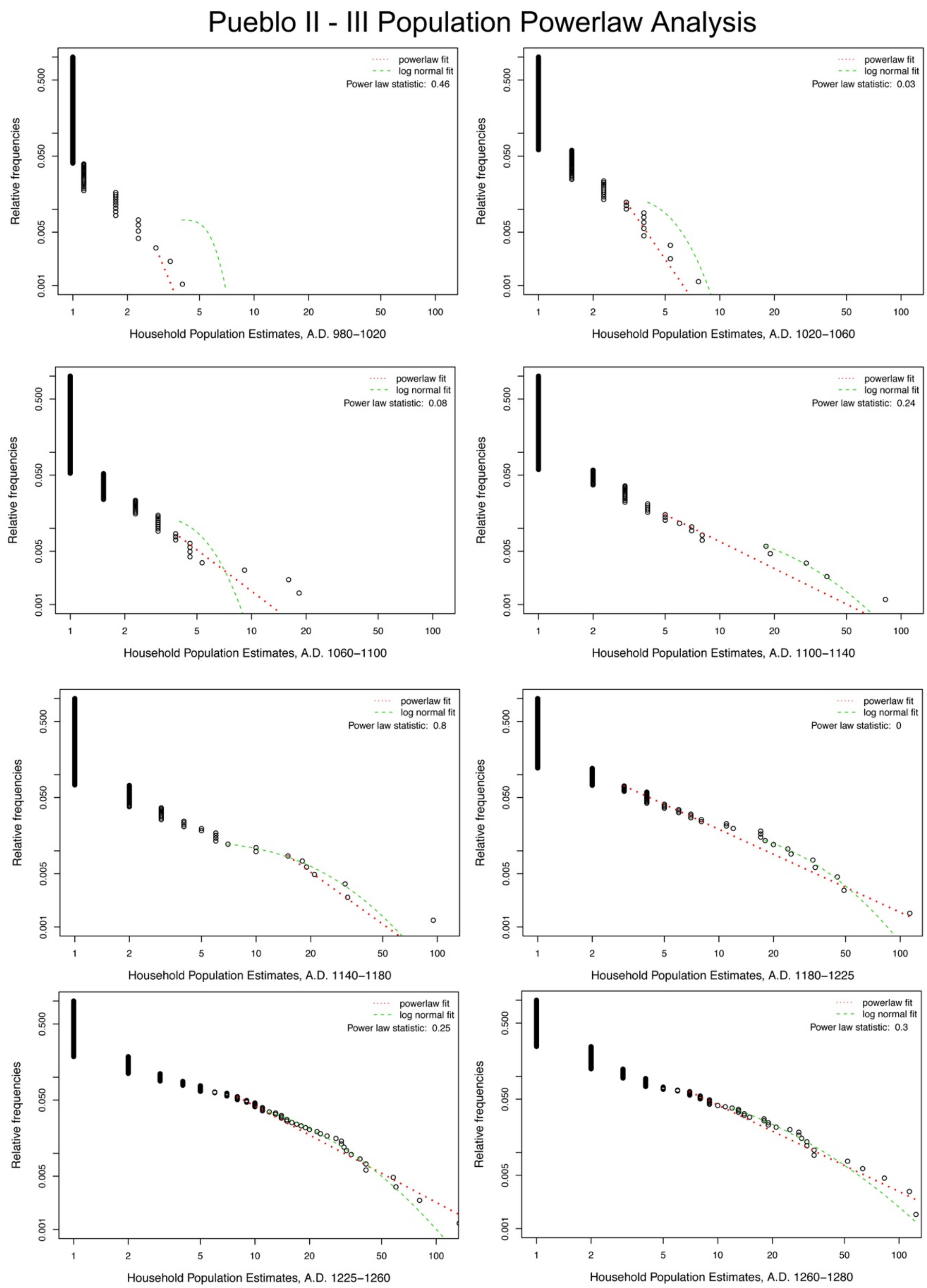


Figure S.4.0.4. Power-law analysis of PII to PIII Momentary Households in the VEPIIN study area.

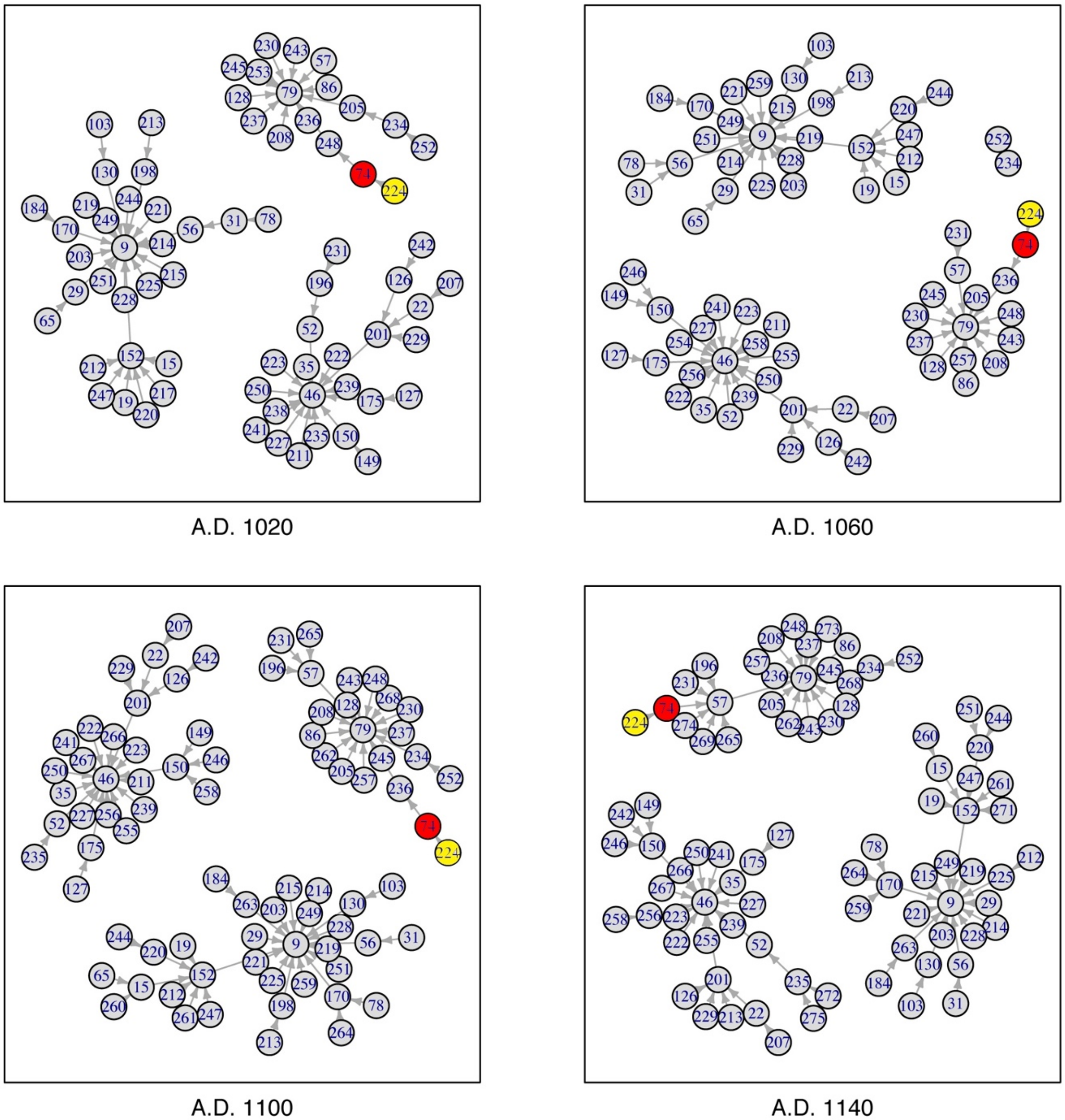


Figure S.4.0.5. Graphs through time of hierarchical relationships within complex groups (Run 1). Centers of groups do not correspond to geographic locations but are chosen to minimize overlap and crowding of nodes. To illustrate possible dynamics we highlight two nodes (simple groups). Group 74 (in red) frequently revolts, and becomes subordinate to three different groups (248, 236, and 57) during the 120 years represented in these panels. Node 224, however, never successfully revolts from node 74 and stays its subordinate throughout the period graphed.

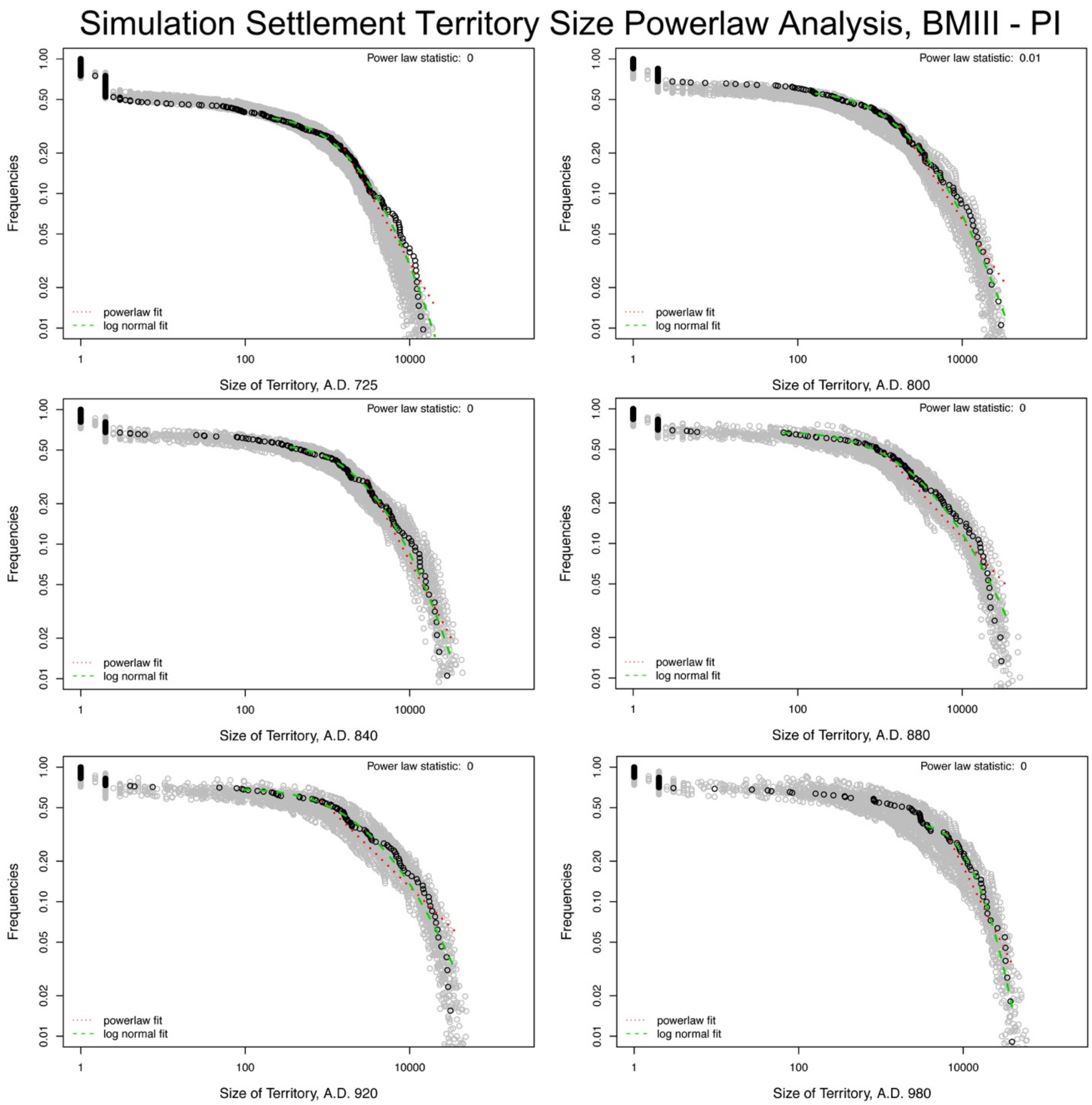


Figure S.4.0.6. Power-law analysis of BMIII to PI simulated group territory sizes.

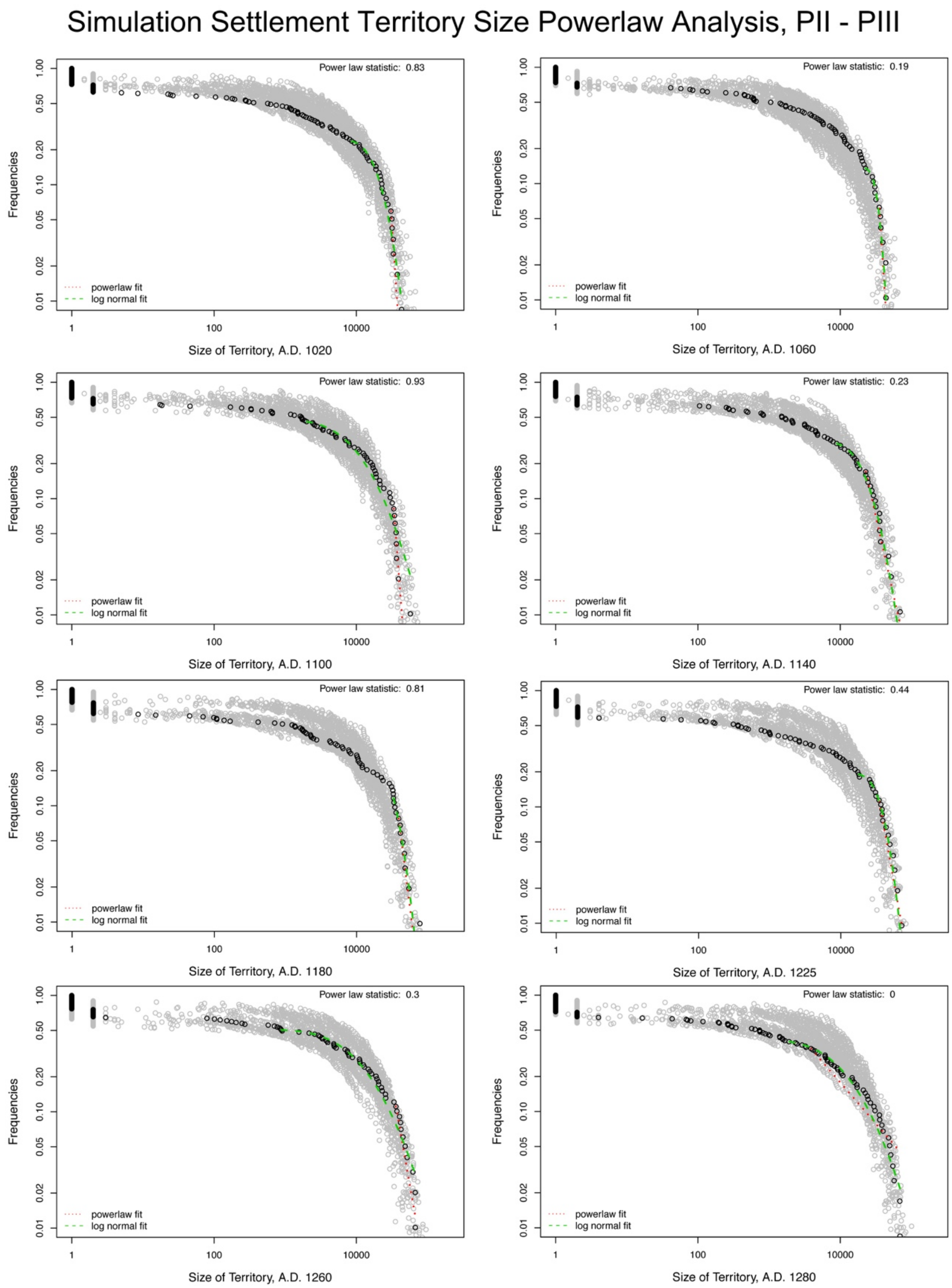


Figure S.4.0.7. Power-law analysis of PII to PIII simulated group territory sizes.

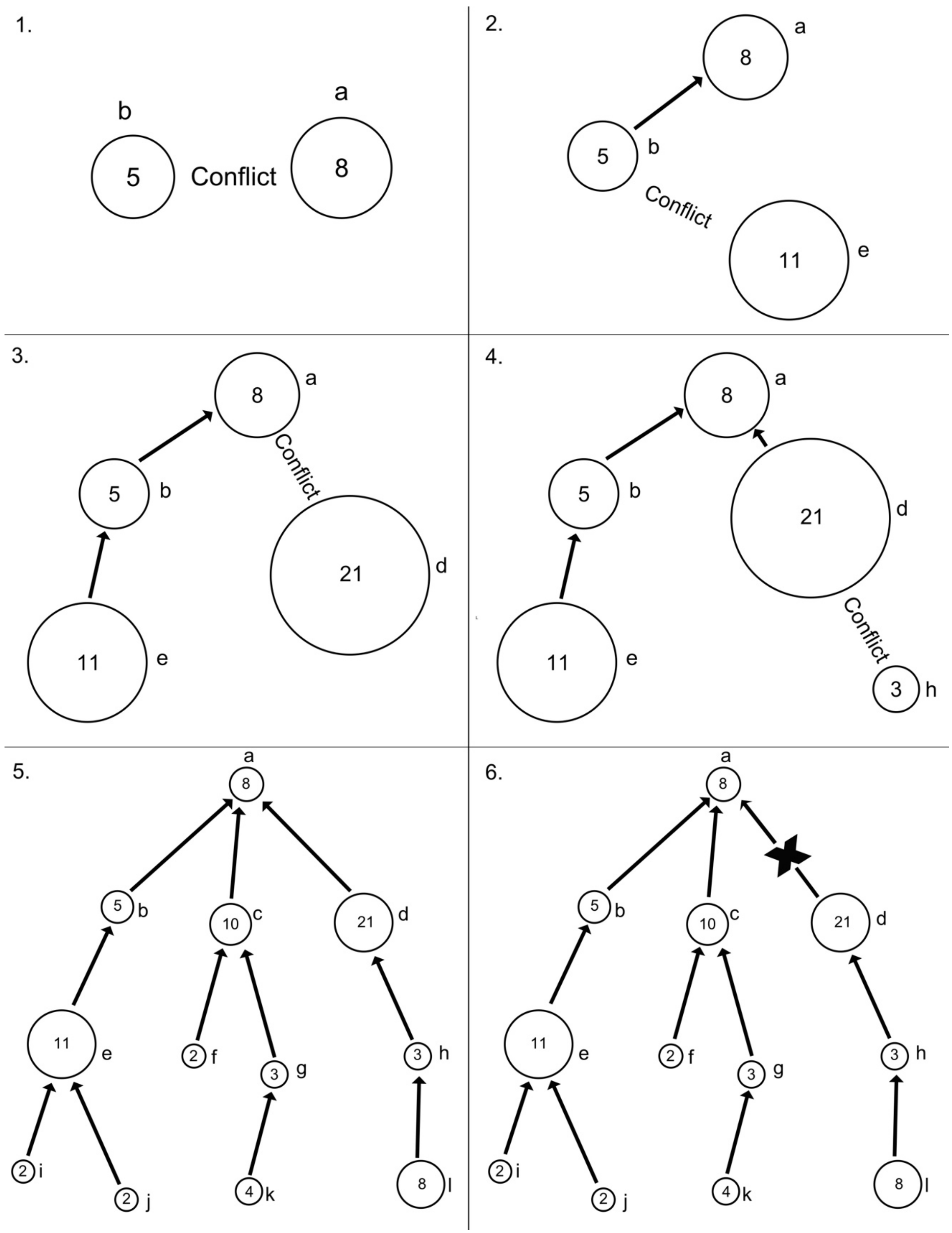


Figure S.4.8. The growth of a polity through time with an attempted revolt. Panel 1 demonstrates conflict between group a, with 8 fighters, and group b, with 5. In panel 2 groups a and b have merged into a complex group with a as the dominant. Group e and group b then come into conflict, and group a mobilizes its fighters to help group b in the conflict. In panel 3 group e has become the subordinate of group b, even though it has more fighters (though not as many as ba and a together). Group d and group a then come into conflict, pitting the 21 fighters from group d against the 24 fighters in the complex group a, b, and e. In panel 4 group d has merged to group a as its subordinate, even though it has more fighters than group a, due to the chain of hierarchy with group a to b to e. When group h comes into conflict with group d it is easily subsumed as a subordinate group to group d. Between panels 4 and 5 many conflicts occur, creating the large polity in panel 5. In panel 6, group d considers revolt from group a. Group d counts its own fighters, as well as the fighters of groups h and l, adding to 32. Group a counts its fighters, as well as the fighters from groups c, d, e, f, g, i, j, and k, adding to 47. Even though group d is larger than group a, since group d cannot coordinate a revolt with groups b and c, defeat is certain if group a and d were to fight, so group d does not revolt.

Supplemental Tables for Chapter Five

Supplemental Tables 1 and 3 are Excel files and will be submitted electronically.

Table S.2. Bones recovered from each of the archaeological assemblages for four species that indicate changing ecosystems.

	Elk	Snowshoe Hare	Sandhill Crane	Scaled Quail
Grass Mesa Pueblo	3	8	1	0
Albert Porter Pueblo	0	0	0	0
Sand Canyon Pueblo	0	0	4	3

References

Adams, K. R.
2015 Plant use. *The Archaeology of Albert Porter Pueblo: A Great House Community Center in Southwestern Colorado*, Susan C. Ryan, *Ed*. Electronic document, www.crowcanyon.org/albertporter, last accessed 05/01/2016.

Adams, K. R., K. L. Petersen.
1999 Environment. In *Colorado prehistory: A context for the southern Colorado river basin*, edited by W. D. Lipe, M. D. Varien, R. H. Wilshusen, pp.14-50. Colorado Council for Professional Archaeologists, Denver.

Adler, Michael A. and Richard H. Wilshusen
1990 Large-scale integrative facilities in tribal societies: Cross-cultural and southwestern U.S. examples. *World Archaeology* 22:133-146.

Aitchison, J. and J. A. C. Brown
1957 *The Lognormal Distribution with special reference to its uses in economics*. University of Cambridge Department of Applied Economics Monograph 5.

Albert, R., H. Jeong, and A.-L. Barabási
1999 Internet: Diameter of the World-Wide Web. *Nature* 401:130-131. doi:10.1038/43601.

Alberti, Gianmarco
2014 Modeling Group Size and Scalar Stress by Logistic Regression from an Archaeological Perspective. *PLoS ONE* 9(3): e91510. doi:10.1371/journal.pone.0091510.

Allen, Craig
2004 Ecological patterns and environmental change. In *Archaeology of Bandelier National Monument: Village Formation on the Pajarito Plateau, New Mexico*, edited by Timothy A. Kohler, pp. 19-67. University of New Mexico Press, Albuquerque, NM.

Allen, W. L., and Richardson, J. B., III
1971 The reconstruction of kinship from archaeological data: The concepts, the methods, and the feasibility. *American Antiquity* 36: 41–53.

ASPCA, American association for the prevention of cruelty to animals.
2015 *Predatory behavior in dogs, technical report*. https://www.aspca.org/pet-care/virtual-pet-behaviorist/dog-behavior/predatory-behavior-dogs.

Auerbach, F.
1913 Das Gesetz der Bevolkerungskonzentration. *Petermans Geographische Mitteilungen* LIV: 73-75.

Backstrom, L., & Kleinberg, J.
2013 Romantic Partnerships and the Dispersion of Social Ties: A Network Analysis of Relationship Status on Facebook. *Proceedings of the 17th ACM Conference on Computer Supported Cooperative Work and Social Computing (CSCW)*, pp. 831-841, New York, NY.

Badenhorst, S., J. C. Driver
2015 Faunal remains. *The Archaeology of Albert Porter Pueblo: A Great House Community Center in Southwestern Colorado*, S. C. Ryan, Ed, Electronic document, www.crowcanyon.org/albertporter.
2009 Faunal changes in farming communities from Basketmaker II to Pueblo III (A.D. 1-1300) in the San Juan Basin of the American Southwest. *Journal of Archaeological Science* 36:1832-1841.

Bala, G. K. Caldeira, M. Wickett, T. J. Phillips, D. B. Lobell, C. Delire, A. Mirin
2007 Combined climate and carbon-cycle effects of large-scale deforestation. *Proceedings of the National Academy of Sciences* 104:6550 –6555.

Benson, L. V.
2011 Factors Controlling Pre-Columbian and Early Historic Maize Productivity in the American Southwest, Part 1: The Southern Colorado Plateau and Rio Grande Regions: *Journal of Archaeological Method and Theory,* 18:1-60.

Benson, L. V., K. Petersen, J. Stein
2007. Anasazi (Pre-Columbian Native-American) Migrations During The Middle-12th and Late-13th Centuries – Were they Drought Induced? *Climate Change* 83(1), pp. 187-213.

Bentley, R. Alexander and Herbert D. G. Maschner
2008 Complexity Theory. In *Handbook of Archaeological Theories*, edited by R. Alexander Bentley, Herbert D.G. Maschner and Christopher Chippendale, pp. 245-270. Alta Mira Press, Lanham, MD.

Bernardini, Wesley
1996 Transitions in Social Organization: A Predictive Model from Southwestern Archaeology. *Journal of Anthropological Archaeology* 15:372–402.

Bettencourt Luis M. A.
2013 The Origins of Scaling in Cities. *Science* 340:1438–1441.

Bettencourt, Luis M. A., Jose Lobo, Dirk Helbing, Christian Kühnert, Geoffrey B. West
2007 Growth, innovation, scaling, and the pace of life in cities. *Proceedings of the National Academy of Sciences* 104:7301-7306.

Binford, Lewis R.
1965 Archaeological systematics and the study of culture process. In *Contemporary Archaeology*, ed. by M. Leone, pp. 125-132. Southern Illinois University, Carbondale.

Bintliff, John
2013 The Hellenistic to Roman Mediterranean: A proto-capitalist revolution? *Economic Archaeology, from structure to performance in European Archaeology*. Edited by T. Kerig and A. Zimmermann, pp. 285-292. Rudolf Habelt, Bonn, Germany.

Binzer, A., U. Brose, A. Curtsdotter, A. Eklöf, B.C. Rall, J.O. Riede, and F. De Castro.
2011 The susceptibility of species to extinctions in model communities. *Basic and Applied Ecology* 12(7):590-599.

Bocinsky, R. Kyle
2014 Landscape-based Null Models for Archaeological Inference. Unpublished Ph.D. dissertation, Department of Anthropology, Washington State University, Pullman, Washington.

Bocinsky, R.K., J. A. Cowan, T. A. Kohler, C. D. Johnson
2012. How hunting changes the VEP world, and how the VEP world changes hunting. *Emergence and Collapse of Early Villages*. Edited by T. A. Kohler and M. D. Varien, pp. 145-152. University of California Press, Berkeley, CA.

Bocinsky, R. Kyle, and Timothy. A. Kohler
2015 Complexity, rigidity, and resilience in the Ancient Puebloan Southwest, *Viewing the Future in the Past: Historical Ecology Applications to Environmental Issues*, edited by H. T. Foster II, L. Paciulli, D. Goldstein. University of South Carolina Press, Columbia, South Carolina.
2014 A 2,000-year reconstruction of the rain-fed maize agricultural niche in the US Southwest. Nature Communications, 5:5618.

Bocinsky, R. Kyle, Johnathan Rush, Keith W. Kintigh, and Timothy A. Kohler
2016 Exploration and exploitation in the macrohistory of the pre-Hispanic Pueblo Southwest. *Science Advances* 2: e1501532.

Bonhommeau, S., L. Dubroca, O. Le Pape, J. Barde, D. M. Kaplan, E. Chassot, A. Nieblas
2013 Eating up the world's food web and the human trophic level. *Proceedings of the National Academy of Sciences* 110: 20617-20620.

Box, G. E. P. & Draper, N. R.
1987 *Empirical Model-Building and Response Surfaces*. Wiley Series in Probability and Statistics.

Breternitz, D. A., C. K. Robinson, and G. T. Gross (compilers)
1986 Dolores Archaeological Program: Final Synthetic Report. USDI Bureau of Reclamation, Engineering and Research Center, Denver. (NTIS PB88130356/AS).

Briggs, Daphne Nash
2003 Metals, Salt, And Slaves: Economic Links Between Gaul and Italy From The Eighth To The Late Sixth Centuries BC. *Oxford Journal of Archaeology* 22(3), pp. 243–259.

Brose, U.
2011. Extinctions in complex size-structured communities. *Basic and Applied Ecology* 12(7):557-561.

Brown, Clifford T., April A. Watson, Ashley Gravlin-Beman, and Larry S. Liebovitch
2012 Poor Mayapan. In *The Ancient Maya of Mexico: Reinterpreting the Past of the Northern Maya Lowlands,* edited by Geoffrey E. Braswell, pp. 306-324. Equinox Publishing Ltd, Bristol CT.

Brughmans, Tom
2010 Connecting the dots: towards archaeological network analysis. Oxford Journal of Archaeology, 29(3): 277–303.
2012 Thinking Through Networks: A Review of Formal Network Methods in Archaeology. *Journal of Archaeological Method and Theory*, 20:623-662.

Brumfield, Elizabeth M., & Earle, Timothy K.
1987 Specialisation, exchange and complex societies. Cambridge: Cambridge University Press.

Cahill, Nicholas
2002 Household and City Organization at Olynthus. Yale University Press, New Haven, CT.

Camerano, Lorenzo
1880 Dell' equilibrio dei viventi mercè la reciproca distruzione. *Atti della Reale Accademia delle Scienze du Torino* 15:393–414.

Cameron, Cathy
2009 Chaco and After in the Northern San Juan. University of Arizona Press, Tucson.

Carballo, David M., Paul Roscoe, and Gary M. Feinman
2014 Cooperation and Collective Action in the Evolution of Complex Societies. *Journal of Archaeological Method and Theory* 21:98-133.

Cederman, Lars-Erik
2002 Endogenizing geopolitical boundaries with agent-based modeling. *PROCEEDINGS OF THE NATIONAL ACADEMY OF SCIENCES* 99:7296-7303.

Cegielski, Wendy H., and J. Daniel Rogers
2016 Rethinking the Role of Agent-Based Modeling in Archaeology. *Journal of Anthropological Archaeology* 41:283–298

Chadwick, J.
1990. The Pech Maho lead. *Zeitschrift für Papyrologie und Epigraphik* 82:161-166.

Childe, V. Gordon
1936 Man Makes Himself. Watts and Co. London, England.

Clarke, David L.
1972 Models and Paradigms in Contemporary Archaeology. *In* Models in Archaeology. Methuen & Co, Ltd. London, U.K. pp. 1-60.

Clauset, Aaron, Cosma Rohilla Shalizi, and M. E. J. Newman
2009 Power-Law Distributions in Empirical Data. *SIAM Review* 51(4):661-703.

Cockburn, Denton, Stefani A. Crabtree, Ziad Kobti, Timothy A. Kohler, R. Kyle Bocinsky
2013 Simulating Social and Economic Specialization in Small-Scale Agricultural Societies. JASSS 16(4) 4.

Coffey, Grant
2016 Creating symmetry: The cultural landscape in the Sand Canyon locality, Southwestern Colorado. *Kiva*, 82(1):1-21.
2014 The Harlan Great Kiva Site: Civic Architecture and Community Persistence in the Goodman Point area of Southwestern Colorado. *Kiva* 79:380-404 DOI: 10.1179/0023194014Z.00000000031.

Coll, M., A. Schmidt, T.N. Romanuk, and H. Lotze.
2011 Food-web structure of seagrass communities across different spatial scales and human impacts. *PLoS One* 6(7):e22591.

Collar, A. C. F.
2007 Network theory and religious innovation. Mediterranean Historical Review, 22(1), 149–162.

Coltrain, Joan Brenner, Joel C. Janetski and Shawn W. Carlyle
2006 The Stable and Radio-Isotope Chemistry of Eastern Basketmaker and Pueblo Groups in the Four Corners Region of the American Southwest: Implications for Anasazi Diets, Origins, and Abandonments in Southwestern Colorado. In *Histories of Maize: Multidisciplinary Approaches to the Prehistory, Linguistics, Biogeography, Domestication, and Evolution of Maize*, edited by John E. Staller, Robert H. Tykot and Bruce F. Benz, pp. 276-289. Elsevier.

Cordell, Linda S., and Fred Plog
1979 Escaping the Confines of Normative Thought: A Reevaluation of Puebloan Prehistory. *American Antiquity* 44:405-429.

Costopoulos, A., Lake, M. and Gupta, N.
2010 Introduction. *In* Costopoulos and Lake (ed.), *Simulating Change – Archaeology into the Twenty-First Century*, University of Utah Press, Salt Lake City, UT. pp. 1-12.

Cowan, J. A., T. A. Kohler, C. D. Johnson, K. Cooper, R. K. Bocinsky.
2012 *Emergence and Collapse of Early Villages*, T. A. Kohler, M. D. Varien, Eds, University of California Press, Berkeley, pp. 129-144.

Coward, Fiona, and R. I. M. Dunbar
2014 Communities on the Edge of Civilization. In *Lucy to Language: The Benchmark Papers*, edited by R. I. M. Dunbar, Clive Gamble, and J. A. J. Gowlett, pp. 380-405. Oxford University Press, Oxford.

Crabtree, Stefani A
2015 "Inferring Social Networks from Aggregation in, and Simulation of, the Central Mesa Verde." *in special issue:* The Connected Past. Journal of Archaeological Method and Theory, 22(144-181).

Crow Canyon Archaeological Center
2004 The Sand Canyon Pueblo Database. Available: http://www.crowcanyon.org/sandcanyondatabase.

De Hoz, J.
1987 El Sec: les graffites mercantiles en Occident et l'éprave de l'El Sec. *Revue des Etudes Anciennes* 89(3-4):117-130.

Dean, J. S.
2004 Anthropogenic Environmental Change in the Southwest as Viewed from the Colorado Plateau. *The Archaeology of Global Change: the Impact of Humans on their Environment.* C. L. Redman, S.R. James, P. R. Fish, J. D. Rogers Eds. (Smithsonian Institution Books, Washington D.C, 2004).

Dean, R. M.
2007 Hunting intensification and the Hohokam "collapse". *Journal of Anthropological Archaeology*26, 1, pp. 109–132 (2007).

Decker, K. W., L. L. Tieszen
1989. Isotopic Reconstruction of Mesa Verde Diet from Basketmaker III to Pueblo III. *Kiva*55, 1, pp. 33-46.

Diaz, S., M. Cabido
1997. Plant functional types and ecosystem function in relation to global change. Journal of Vegetation Science, 8, 463–474.

Dietler Michael
1990 Driven by Drink: The Role of Drinking in the Political Economy and the Case of Early Iron Age France. *Journal of Anthropological Archaeology* 9: 352-406.
2010 *Archaeologies of Colonialism: Consumption, Entanglement, and Violence in Ancient Mediterranean France*. University of California Press, Los Angeles, CA.

Diodorus Siculus
1939 *The Library of Hisotory, Volume III, Books 4.59-8.* Translated by C.H. Oldfather. Loeb Classical Library. Harvard University Press, Cambridge, MA.

Drennan, Robert D.
2009 *Statistics for Archaeologists: A Common Sense Approach.* Springer, New York, NY.

Driver, J. C.
2011. Human impacts on animal populations in the American Southwest. *Movement, Connectivity and Landscape Change in the Ancient Southwest*, M.C. Nelson, C. Strawhacker, Eds, University Press of Colorado, Boulder, pp. 179-198.

Driver, J. C., J. Woiderski
2008 Interpretation of the "lagomorph index" in the American Southwest. *Quaternary International*185, pp. 3-11 (2008).

Duffy, Paul R.
2015 Site size hierarchy in middle-range societies. *Journal of Anthropological Archaeology* 37:85-99.

Dunbar, R. I. M.
2008 Mind the Gap: or Why Humans Aren't Just Great Apes. *Proceedings of the British Academy* 154:403-423.

Dunne, J.A., H. Maschner, M. W. Betts, N. Huntly, R. Russell, R.J. Williams, S.A. Wood
2016 The roles and impacts of human hunter-gatherers in North Pacific marine food webs. *Scientific Reports 6,* pp. 1-9, DOI: 10.1038/srep21179

Dunne, J.A., K.D. Lafferty, A.P. Dobson, R.F. Hechinger, A.M. Kuris, N.D. Martinez, J.P. McLaughlin, K.N. Mouritsen, R. Poulin, K. Reise, D.B. Stouffer, D.W. Thieltges, R.J. Williams, and C.D. Zander
2013 Parasites affect food web structure primarily through increased diversity and complexity. *PLoS Biology* 11:e1001579.

Dunne, J. A., R.J. Williams, N.D. Martinez, R.A. Wood, D.E. Erwin
2008 Compilation and network analyses of Cambrian food webs. *PLoS Biology*6, pp. 693-708. doi: 10.1371/journal.pbio.0060102.

Dunne, J.A. R. J. Williams, N.D. Martinez
2002a Network structure and biodiversity loss in food webs: robustness increases with connectance. *Ecology Lett* 5: 558–567.
2002b Food-web structure and network theory: the role of connectance and size. *Proc Natl Acad Sci USA*99, pp. 12917–12922.

Earle, T.
1997 <u>How Chiefs Come to Power: The Political Economy in Prehistory</u>. Stanford: Stanford University Press 1997.

Eco, Umberto

2000. Baudolino. Harcourt, Inc. New York NY.

Egerton, F. N.
2007 Understanding food chains and food webs, 1700-1970. *Bulletin of the Ecological Society of America* 88: 50–69.

Epstein, A. L.
1969 Gossip, norms and social network. In J. C. Mitchell (Ed.), Social networks in urban situations: analyses of personal relationships in Central African towns. Manchester: Manchester University Press.

Estes, J. A., M. T. Tinker, T. M. Williams, D. F. Doak
1998 Killer Whale Predation on Sea Otters Linking Oceanic and Nearshore Ecosystems. *Science* 282(5388):473-476.

Evans, Sarah and Kathrin Felder (Editors)
2014 Social Network Perspectives in Archaeology. *The Archaeology Review from Cambridge*. 29(1).

Favory, François, Jean-Luc Fiches, Claude Raynaud
1998 La dynamique de l'habitat gallo-romain dans la basse vallée du Rhône. In Archaeomedes (collective publisher), *Des oppida aux métropoles,* Paris, France. pp. 73-116.

Favory, François, Jean-Jacques Girardot, Laure Nuninger, François-Pierre Tourneux,
1999 « Archaeomedes : une étude de la dynamique de l'habitat rural en France méridionale, dans la longue durée (800 av. J.-C.-1600 ap. J.-C.) », *AGER*, (9), pp. 15–35.

Fiorenza, M., L. Benedetti-Cecchi, S.Gambaccini, I. Bertocci, C. Borsini, G. Chato Osio, F. Romano
2005 Cascading human impacts, marine protected areas, and the structure of Mediterranean reef assemblages, *Ecological Monographs* 75:81–102.

Firestone, R. B., A. West, J. P. Kennett, L. Becker, T. E. Bunch, Z. S. Revay, P. H. Schultz, T. Belgya, D. J. Kennett, J. M. Erlandson, O. J. Dickenson, A. C. Goodyear, R. S. Harris, G. A. Howard, J. B. Kloosterman, P. Lechler, P. A. Mayewski, J. Montgomery, R. Poreda, T. Darrah, S. S. Que Hee, A. R. Smith, A. Stich, W. Topping, J. H. Wittke and W. S. Wolbach
2007 Evidence for an extraterrestrial impact 12,900 years ago that contributed to the megafaunal extinctions and the Younger Dryas cooling. *PROCEEDINGS OF THE NATIONAL ACADEMY OF SCIENCES*104, 41, pp. 16016–16021.

Flannery, Kent V. (Ed.)
1976 *The Early Mesoamerican Village*. Academic Press, New York, NY.

Flannery, Kent, and Joyce Marcus
2012 *The Creation of Inequality: How our Prehistoric Ancestors set the Stage for Monarchy, Slavery, and Empire*. Harvard University Press, Cambridge.

Flint-Lacey, P.R.
2003. The Ancestral Puebloans and their piñon–juniper woodlands. *Ancient Piñon–Juniper Woodlands,* M.L. Floyd, Ed., pp. 309–320. University Press of Colorado, Boulder, CO.

Fovet, Elise
2005 *Dynamique spatiale du peuplement et analyse des ressources agro-pastorales dans le basin de Combas et le vallon de l'Aigalade (Gard, France), du Bronze final au bas Moyen-Âge. Temps et espaces de l'homme en société, analyses et modèles spatiaux en archéologie XXV*[e] *rencontres internationales d'archéologie et d'histoire d'Antibes*. Sous la direction de J-F. Berger, F. Bertoncello, F. Braemer, G. Davtian, M. Gazenbeek. Éditions APDCA, Antibes.

Fowles, Severin
2010 People Without Things. In *An Anthropology of Absence: Materializations of Transcendence and Loss*. Mikkel Bille, Frida Hastrup, Tim Flohr Soerensen (Eds.). Springer Science and Business Media.
2013 *An Archaeology of Doings: Secularism and the Study of Pueblo Religion*. SAR Press, Santa Fe.

Freeman, L. C.
2004 *The development of social network analysis*. Empirical Press, Vancouver.

Fried, M.
1967 *The Evolution of Political Society: An Essay in Political Anthropology*. Random House. New York, NY.

Fritts, T.H., G.H. Rodda
1998 The role of introduced species in the degradation of island ecosystems: a case history of Guam. *Annual Review of Ecology and Systematics* 29:113–140.

Froese, T., Gershenson, C., & Manzanilla, L. R.
2014 Can Government Be Self-Organized? A Mathematical Model of the Collective Social Organization of Ancient Teotihuacan, Central Mexico. *PloS one*, 9/10: e109966. DOI: 10.1371/journal.pone.0109966

Garcia, Dominique
2005 Urbanization and Spatial Organization in Southern France and North-Eastern Spain during the Iron Age. Mediterranean Urbanization 800–600 BC, Proceedings of the British Academy, Robin Osborne and Barry Cunliffe (eds). p. 169–186.
2014 *La celtique méditerranéenne : Habitats et sociétés en Languedoc et en Provence VIIIe–II*[e] *siècles av. J.-C.*, Deuxième édition revue et augmentée, Paris, Éditions Errance, 247.

Gauthier, Estelle, Olivier Weller, Laure Nuninger, Meréva Gabillot, Bénédicte Quilliec, et Pierre Pétrequin
2008 *Models for the study of the consumption and the circulation of resources and products in France and Western Europe during the Neolithic and the Bronze Age* (Programme ArchaeDyn). ArchaeDyn: 7 millenia of territorial dynamics, settlement pattern, production and trades from Neolithic

to Middle Ages. Spatial dynamics of settlement and natural resources: toward an integrated analysis over the long term from Prehistory to Middle Ages, conference reports.

Gehlhausen, Sophia M., Mark W. Schwartz, Carol K. Augspurger
2000 Vegetation and microclimatic edge effects in two mixed-mesophytic forest fragments. *Plant Ecology* 147:21-35.

Gemmell, N. J., M. K. Schwartz, B. C. Robertson
2004 Moa were many. *Proc Biol Sci*. 2004271(Suppl 6), pp. S430–S432.

Gillespie, Colin S.
2015 Fitting Heavy Tailed Distributions: The powerRlaw Package. *Journal of Statistical Software* 64:1-16.

Glowacki, Donna M.
2015 *Living and Leaving: A Social History of Regional Depopulation in Thirteenth-Century Mesa Verde*. The University of Arizona Press, Tucson.

Glowacki, Donna M., and Scott G. Ortman
2012 Characterizing Community-Center (Village) Formation in the VEP Study Area, A.D. 600-1280. In *Emergence and Collapse of Early Villages: Models of Central Mesa Verde Archaeology*, edited by Timothy A. Kohler and Mark D. Varien, pp. 219-246. University of California Press, Berkeley.

Gras, M.
1985 Trafics tyrrhéniens archaïques. Bibliothèque des Ecoles Français d'Athènes et de Rome 258. Ecole Française de Rome, Rome.

Griffin, Arthur F., and Charles Stanish
2007 An Agent-based Model of Prehistoric Settlement Patterns and Political Consolidation in the Lake Titicaca Basin of Peru and Bolivia. *Structure and Dynamics: eJournal of Anthropological and Related Sciences* 2:2. http://escholarship.org/uc/item/2zd1t887

Grimm, Volker, Eloy Revilla, Uta Berger, Florian Jeltsch, Wolf M. Mooij, Steven F. Railsback, Hans-Hermann Thulke, Jacob Weiner, Thorsten Wiegand, Donald L. DeAngelis
2005 Pattern-Oreinted Modeling of Agent-Based Complex Systems: Lessons from Ecology. *Science* 301(5750), pp. 987-991.

Grove, Matt
2011 An archaeological signature of multi-level social systems: The case of the Irish Bronze Age. *Journal of Anthropological Archaeology*, 30, pp. 44-61.

Gruner, Erina

2015 Replicating Things, Replicating Identity: The Movement of Chacoan Ritual Paraphernalia Beyond the Chaco World. In *Practicing Materiality*, edited by Ruth M. Van Dyke, pp. 56–78. University of Arizona Press, Tucson.

Haas, W. Randall, Jr., Cynthia J. Klink, Greg J. Maggard, and Mark S. Aldenderfer
2015 Settlement-Size Scaling among Prehistoric Hunter-Gatherer Settlement Systems in the New World. *PLoS One*, 10(11): e0140127. doi:10.1371/journal.pone.0140127

Hadid, Diaa and Joseph Krauss
2014 Iraqis Join what UN says is largest worldwide displaced population since WWII. *US News and World Report. http://www.usnews.com/news/world/articles/2014/06/20/un-number-of-worlds-displaced-over-50-million*

Hamilton, Marcus, Bruce T. Milne, Robert S. Walker, Oskar Burger and James H. Brown
2007 The complex structure of hunter-gatherer social networks. *Proceedings of the Royal Society B: Biological Sciences* 274:2195-2202.

Hanneman, Robert A., and Mark Riddle.
2005 *Introduction to social network methods*. CA: University of California Riverside, published in digital form at http://faculty.ucr.edu/~hanneman/.

Hashim, Muhammad Nazlida and Che Razak, Razli
2004 Consumer ethnocentrism: the relationship with domestic products evaluation and buying preferences. *International Journal of Management Studies (IJMS)* 11:29-44.

Hegmon, Michelle
2008 Structure and Agency in Southwest Archaeology. In *The Social Construction of Communities: Agency, Structure, and Identity in the Prehispanic Southwest*, edited by Mark D. Varien and James M. Potter, pp. 217-231. Alta Mira Press, Rowman & Littlefield Publishers, Plymouth UK.

Heitman, Carrie C.
2015 The House of our Ancestors: New Research on the Prehistory of Chaco Canyon, New Mexico, A.D. 800-1200. In *Chaco Revisited: New Research on the Prehistory of Chaco Canyon, New Mexico*, edited by Carrie C. Heitman and Stephen Plog, pp. 215-248. University of Arizona Press, Tucson.

Herring, E.M., R. S. Anderson, G. L. San Miguel
2014 Fire, vegetation and Ancestral Puebloans: A sediment record from Prater Canyon in Mesa Verde National Park, Colorado, U.S.A., *The Holocene,* pp. 1-11.

Hobbes, Thomas
1651 *Leviathan. Revised Edition*, eds. A.P. Martinich and Brian Battiste. Peterborough, ON: Broadview Press, 2010.

Holling, C. S.

1973 Resilience and stability of ecological systems *Annual Review of Ecology and Systematics* 4:1-23.

Hooper, P. L., Kaplan, H. S., Boone, J. L.
2010 A theory of leadership in human cooperative groups. *Journal of Theoretical Biology* 265:633-646.

Horton, Robert E.
1945 Erosional development of streams and their drainage basins: Hydro-physical approach to quantitative morphology. G*eological Society of America Bulletin* 56:275–370.

Jackson, R. B., E. G. Jobbágy, M. D. Nosetto
2009. Ecohydrology in a human-dominated landscape. *Ecohydrology* 2:383–389.

Johnson, Allen W., and Timothy K. Earle
2000 *The Evolution of Human Societies: From Foraging Group to Agrarian State*. Stanford University Press, Stanford.

Johnson, Gregory A.
1982 Organizational Structure and Scalar Stress. In *Theory and Explanation in Archaeology*, edited by C. Renfrew, M.J. Rowlands, and B.A. Segraves, pp. 389-421. Academic Press, New York.
1989 Dynamics of Southwestern Prehistory: Far Outside—Looking In. In *Dynamics of Southwest Prehistory*, edited by Linda S. Cordell and George J. Gumerman, pp. 371-389. Smithsonian Institution Press, Washington, D.C.

Judge, W. James
1989 Chaco Canyon—San Juan Basin. In *Dynamics of Southwest Prehistory*, edited by Linda S. Cordell and George J. Gumerman, pp. 209-261. Smithsonian Institution Press, Washington, D.C.

Kantner, John
2003 Rethinking Chaco as a System. *Kiva* 69(2): 207-227.

Kantner, John and Ronald Hobgood
2003 Digital Technologies and prehistoric landscapes in the American Southwest. In *The reconstruction of archaeological landscapes through digital technologies*, number 1151 in BAR Internatinoal Series, M. Forte, P. R. Williams and J. Wiseman (Eds.). pp. 117-123, Oxford: Archaeopress.

Kay, C. E.
1994 Aboriginal Overkill: The role of Native Americans in structuring western ecosystems. *Human Nature* 5:359-398.
1995 Aboriginal overkill and native burning: implications for modern ecosystem management, *Western Journal of Applied Forestry* 10, pp. 121-126.

Keeley, Lawrence H.
1996 *War Before Civilization*. Oxford University Press, Oxford, UK.

Kidder, Alfred V.
1924 *An Introduction to the Study of Southwestern Archaeology*. Yale University Press (Year 2000 Edition).

Kling, G.W.
2015 The flow of energy: Higher trophic levels, Global Change, University of Michigan Lecture.

Klingenstein, Sara, Tim Hitchkock, Simon DeDeo
2014 The Civilizing Process in London's Old Bailey. *Proceedings of the National Academy of Sciences.* 111(26):9419-9424.

Knappett, C., Evans, T., & Rivers, R.
2011 The Theran eruption and Minoan palatial collapse: new interpretations gained from modelling the maritime network. *Antiquity*, 85(329), 1008–1023.

Knops, J.M.H., D. Tilman, N.M. Haddad, S. Naeem, C.E. Mitchell, J. Haarstad, M.E. Ritchie, K.M. Howe, P.B. Reich, E. Siemann, J. Groth.
1999. Effects of plant species richness on invasion dynamics, disease outbreaks, insect abundances and diversity, *Ecology Letters* 2(5), pp. 286-294.

Koehler, C. G.
1978 Corinthian A and B Transport Amphoras. Ph.D. Dissertation. Princeton University, Princeton N.J.

Kohler, T. A.
1983. Dolores archaeological program technical reports, Report Number DAP-084, Cultural Resources Mitigation Program: Dolores Project Bureau of Reclamation, Upper Colorado Region, Contract No. 8-07-40-S0562.
2004. Pre-Hispanic human impact on North American southwestern environments: Evolutionary ecological perspectives, *The Archaeology of Global Change: the Impact of Humans on their Environment.* C. L. Redman, S. R. James, P. R. Fish, J. D. Rogers Eds, (Smithsonian Institution Books, Washington D.C.
2012 Modeling Agricultural Productivity and Farming Effort. In *Emergence and Collapse of Early Villages: Models of Central Mesa Verde Archaeology*, edited by T. A. Kohler and M. D. Varien, pp. 85-111. University of California Press, Berkeley.

Kohler, Timothy A., Stefani A. Crabtree, R. Kyle Bocinsky and Paul Hooper
In review Developing General Methods for Explaining Sociopolitical Evolution in Prehispanic Pueblo Societies. In *The Principles of Complexity*, edited by Jeremy Sabloff et al. Princeton University Press. http://www.santafe.edu/media/workingpapers/15-04-011.pdf

Kohler, Timothy A., Denton Cockburn, Paul Hooper, R. Kyle Bocinsky, and Ziad Kobti
2012 The Coevolution of Group Size and Leadership: An agent-based public goods model for prehispanic Pueblo societies. *Advances in Complex Systems* 15:29.

Kohler, Timothy A., and George Gumerman (editors)
2000 *Dynamics in Human and Primate Societies: Agent-based Modeling of Social and Spatial Presses*. Santa Fe Institute Studies in the Sciences of Complexity. Oxford University Press, New York.

Kohler, Timothy A., and Rebecca Higgins
2016 Quantifying Household Inequality in Early Pueblo Villages. *Current Anthropology* 57(5):690-697.

Kohler, Timothy A., Scott G. Ortman, Katie E. Grundtisch, Carly M. Fitzpatrick and Sarah M. Cole
2014 The Better Angels of Their Nature: Declining Violence Through Time Among Prehispanic Farmers of the Pueblo Southwest. *American Antiquity* 79:444-464.

Kohler, Timothy A. and Kelsey M. Reese
2014 Long and spatially variable Neolithic Demographic Transition in the North American Southwest. *Proceedings of the National Academy of Sciences*. doi: 10.1073/pnas.1404367111

Kohler, Timothy A., and Mark D. Varien, Eds.
2012 *Emergence and Collapse of Early Villages*. University of California Press, Berkeley and Los Angeles, CA.

Kohler, Timothy A., and Mark D. Varien
2010 A Scale Model of Seven Hundred Years of Farming Settlements in Southwestern Colorado. In *Becoming Villagers: Comparing Early Village Societies*, edited by M. Bandy and J. Fox, pp. 37-61. Amerind Foundation and the University of Arizona Press, Tucson.

Kohler, Timothy A., M. D. Varien, A. Wright, and K. A. Kuckelman
2008 Mesa Verde migrations. *American Scientist* 96:146-153.

Kohring, Sheila E.
2012 A scalar perspective to social complexity: Complex relations and complex questions. In T.L. Kienlin and A. Zimmermann (eds.), *Beyond Elites: Alternatives to Hierarchical Systems in Modelling Social Formations*, edited by T.L. Kienlin and A. Zimmermann, Vol.215, pp. 327-337. Universitatsforschungen zur Prahistorischen Archaoligie, Bonn: Ruhr-Universitat.

Kuckelman, K. A.
2010 Catalysts of the thirteenth-century depopulation of Sand Canyon Pueblo and the Central Mesa Verde Region. *Leaving Mesa Verde: Peril and Change in the Thirteenth Century Southwest*, edited by T. A. Kohler, M. D. Varien, A. M. Wright, pp.180-199. University of Arizona Press, Tucson, AZ.

Lake, Mark W.
2014 Trends in Archaeological Simulation. *Journal of Archaeological Method and Theory*, 21(2), 258-287.

LeBlanc, Stephen A.
1999 *Prehistoric Warfare in the American Southwest.* University of Utah Press, Salt Lake City, UT.

Lehman, Julia, Phyllis Lee, and R. I. M. Dunbar
2014 Unravelling the Function of Community-level Organization. In *Lucy to Language: The Benchmark Papers*, edited by R. I. M. Dunbar, Clive Gamble, and J. A. J. Gowlett, pp. 245-276. Oxford University Press, Oxford.

Lekson, Stephen H. (editor)
2006 *The Archaeology of Chaco Canyon, an Eleventh-Century Pueblo Regional Center.* SAR Press, Santa Fe.

Lekson, Stephen H.
2006 Chaco matters: An introduction. *The Archaeology of Chaco Canyon: An Eleventh Century Pueblo Regional Center,* S. H. Lekson, Ed., SAR Press, Santa Fe, NM, pp. 3-44.
2015 *The Chaco Meridian: One Thousand Years of Political and Religious Power in the Ancient Southwest*. 2nd edition. Rowman & Littlefield, Lanham, Maryland.

Lightfoot, Kent G. and Gary M. Feinman
1982 Social Differentiation and Leadership Development in Early Pithouse Villages in the Mogollon Region of the American Southwest. *American Antiquity* 47:64-86.

Lipe, William D.
2002 Social Power in the Central Mesa Verde Region, A.D. 1150-1290. In *Seeking the Center Place: Archaeology and Ancient Communities in the Central Mesa Verde Region*, edited by Mark D. Varien and Richard H. Wilshusen, pp. 203-232. University of Utah Press, Salt Lake City.
2006 Notes from the North. In *The Archaeology of Chaco Canyon: An Eleventh-century Pueblo Regional Center*, edited by Stephen K. Lekson, pp. 261-313. SAR Press, Santa Fe.

Lipe, William D., Bonnie L. Pitblado
1999 Paleoindian and Archaic periods, *Colorado Prehistory: A Context for the Southern Colorado River Basin*, W. D. Lipe, M. D. Varien, R. H. Wilshusen, Eds., Colorado Council of Professional Archaeologists, Crow Canyon Archaeological Center Cortez, CO, pp. 95-131.

Lotze, H. K., M. Coll, J. Dunne
2011 Historical changes in marine resources, food-web structure and ecosystem functioning in the Adriatic Sea, Mediterranean. *Ecosystems* 14:198–222.

Lyman, Lee R
2009 *Prehistory of the Oregon Coast: The Effects of Excavation Strategies and Assemblage Size on Archaeological Inquiry*. Left Coast Press, Walnut Creek.

Mahoney, Nancy M., and John Kantner
2000 Chacoan Archaeology and Great House Communities. *Great House Communities Across the Chacoan Landscape*, edited by John Kantner and Nancy M. Mahoney, pp. 1-18. University of Arizona Press, Tucson.

Maran, J.
2009 The Crisis Years? Reflections on Signs of Instability in the Last Decades of the Mycenaean Palaces. *Scienze dell'antichità: Storia archeologia antropologia* 15:241-262.

Martinez, N., J. Dunne, P. Kirch, N. Davies, J. Kahn.
Award dates (2013-2017). Coupled Human and Natural Systems Grant, CNH: Socio-Ecosystem Dynamics of Human-Natural Networks on Model Islands, Award Abstract #1313830, National Science Foundation, http://www.nsf.gov/awardsearch/showAward?AWD_ID=1313830.

Maschner H, M Betts, J Cornell, J Dunne, B Finney, N Huntly, J Jordan, A King, K Reedy-Maschner, R Russell, S Wood.
2009 An Introduction to the Biocomplexity of Sanak Island, Western Gulf of Alaska. Pacific Science 63(4):673-709.

Matson, R.G.
2016 The nutritional context of the Pueblo III depopulation of the northern San Juan: Too much maize? *Journal of Archaeological Science: Reports* 5:622–631.

Matthews, M. H.
1988 The macrobotanical data base: Applications in testing two models of socioeconomic change, *Dolores Archaeological Program: Anasazi Communities at Dolores: Grass Mesa Village*, W. D. Lipe, J. N. Morris, T. A. Kohler, Eds. U.S. Department of the Interior, Bureau of Reclamation, Denver, CO.

Mazzeo, Michael J.
2002 Product Choice and Oligopoly Market Structure The RAND Journal of Economics. Vol. 33, No. 2 (Summer, 2002), pp. 221-242

McAllister, Patrick
2006 Xhosa Beer Drinking Rituals: Power, Practice and Performance in the South African Rural Periphery. Durham: Carolina Academic Press, 2006.

McElreath, R., Boyd R.
2007 Mathematical Models of Social Evolution: A Guide for the Perplexed. Univeristy of Chicago Press, Chicago, IL.

McGlade, James
1995 Archaeology and the ecodynamics of human-modified landscapes. *Antiquity* 69(262), pp. 113-132.

McGovern, Patrick E., Benjamin P. Luley, Nuria Rovira, Armen Mirzoian, Michael P. Callahan, Karen E. Smith, Gretchen R. Hall, Theodore Davidson, and Joshua M. Henkin
2013 Beginning of viniculture in France. *Proceedings of the National Academy of Sciences*, 110(25):10147–10152, doi: 10.1073/pnas.1216126110

McGregor, John C.
1943 Burial of an Early American Magician. *Proceedings of the American Philosophical Society* 82(2):270–298.

Mertz, E. T.
1970. Nutritive value of corn and its products, *Corn: Culture, Processing, Products, Major Feed and Food Crops in Agriculture and Food Series,* Edited by G. E. Inglett, pp. 350-359. AVI Publishing Company Incorporated, Roslyn, New York.

Micheli, F., L. Benedetti-Cecchi, S. Gambaccini, I. Bertocci, C. Borsini, G. C. Osio, F. Romano
2005 Cascading human impacts, marine protected areas, and the structure Of Mediterranean reef assemblages, *Ecological Monographs*75, pp. 81–102.

Mills, Barbara J.
2007 Performing the Feast: Visual Display and Suprahousehold Commensalism in the Puebloan Southwest. *American Antiquity* 72:210-239.

Mills, B. J., Clark J. J., Peeples, M. A., Haas, W. R. Jr, Roberts, J. M. Jr, Hill, J. B., Huntley, D. L., Borck, L., Breiger, R.L., Clauset, A., Shackley, M.S.
2013 Transformation of social networks in the late pre-Hispanic US Southwest. *Proceedings of the National Academy of Sciences* 110(15):5785-5790.

Mitchell, Melanie
2009 Complexity, A Guided Tour. Oxford University Press, Oxford, U.K.

Mitzenmacher, Michael
2004 A Brief History of Generative Models for Power Law and Log-Normal Distributions. *Internet Mathematics* 2:226-251.

Mol, Annemarie and John Law
2002 Complexities: an Introduction. In *Complexities: Social Studies of Knowledge Practices (Science and Cultural Theory),* edited by John Law and Annemarie Mol, pp. 1-22. Durham: Duke University Press.

Monleon, V. J., K. Cromack, J. D. Landsberg
1997 Short-and long-term effects of prescribed underburning on nitrogen availability in ponderosa pine stands in central Oregon. Canadian Journal of Forest Research, 27:369–378.

Morel, Jean-Paul

1981 Le Commerce Etrusque en France, en Espagne, et en Afrique. *L'Eturia Mineraria: Atti del XII Convegno di studi etruschi e etalica; Firenze-Populonia-Piombino, 16-20 giugno 1979.* pp 463-508.

Morell, V.
2015 Lessons from the wild lab, *Science* (20) pp. 1302-1307.

Moreno, J. L.
1934 Who shall survive? Washington, DC: Nervous and Mental Disease Publishing .
1946 Sociogram and sociomatrix: a note to the paper by Forsyth and Katz. Sociometry, 9.
1960 The sociometry reader. Glencoe: The Free Press.

Moreno, J. L., & Jennings, H. H.
1938 Statistics of social configurations. Sociometry, 1, 342–374.

Morgan, Lewis Henry
1877 *Ancient Society, or Researches in the Lines of Human Progress from Savagery through Barbarism to Civilization*. Gloucester, MA: Peter Smith.

Morris, Earl H.
1924 Burials in the Aztec Ruin and the Aztec Ruin Annex. *Anthropological Papers of the American Museum of Natural History, Volume XXVI, Parts II and IV*. American Museum of Natural History, New York.

Muir, R. J.
2007. Faunal Remains, *The Archaeology of Sand Canyon Pueblo*. Cortez, CO: Crow Canyon Archaeological Center.

Murphy, G., and T.N. Romanuk
2014 A meta-analysis of local declines in species richness from human disturbances. *Ecology and Evolution* 4:91-103.

Myers, K.
1964 Influence of density on fecundity, growth rates, and mortality in the wild rabbit, *CSIRO Wildlife Research* 9, pp. 134–137.

Nash, S. E.
1999. *Time, Trees, and Prehistory: Tree-Ring Dating and the Development of North American Archaeology, 1914-1950*. Salt Lake City, UT: The University of Utah Press.

Nelson, M. C., G. Schachner.
2002. Understanding abandonments in the North American Southwest. *Journal of Archaeological Research* 10(2):167-206.

Neusius, S. W., M. Gould

1988 Faunal Remains: Implications for Dolores Anasazi Adaptations. *Dolores Archaeological Program: Anasazi Communities at Dolores: Grass Mesa Village*, W. D. Lipe, J. N. Morris, T. A. Kohler, Eds. U.S. Department of the Interior, Bureau of Reclamation, Denver, CO.

Newberry, J. S.
1876. Geological report, *Report of the exploring expedition from Santa Fé, New Mexico, to the junction of the Grand and Green rivers of the great Colorado of the West, in 1859, under the command of Capt. J. N. Macomb, Corps of topographical engineers,* J. N. Macomb, Ed., U.S. Government Printing Office, Washington, D.C.

Newman, M. E. J.
2009 *Networks: An Introduction*. Oxford University Press. Oxford, U.K.

NRCS: National Resources Conservation Service.
1999 American Elk (Cervus elaphus), Fish and Wildlife Habitation Leaflet, Number 11, November.

Nuninger Laure,
2002 « Peuplement et territoires protohistoriques du VIIIe au Ier s. av. J.-C. en Languedoc oriental (Gard-Hérault) », Thèse de doctorat en Archéologie, Université de Franche-Comté [en ligne] https://halshs.archives-ouvertes.fr/tel-00002981/

Nuninger, Laure, Pierre Garmy, Thérèse Libourel, Stefani A. Crabtree, Jean-Luc Fiches, Jacques Ferber
In press Modéliser les mutations territoriales de l'Âge du Fer dans le midi de la Gaule (VIe-Ve siècles av. J.-C.). Presses Universitaires François Rabelais ; Paris, France.

Ortman, S. G.
2012. *Winds from the North: Tewa Origins and Historical Anthropology*. Salt Lake City, UT: The University of Utah Press.
2016 Discourse and Human Securities in Tewa Origins. In *Archaeology of the Human Experience*, edited by Michelle Hegmon, pp. 74-94. Archeological Papers of the American Anthropological Association, Number 27.

Ortman, Scott G., Andrew H. F. Cabaniss, Jennie O. Sturm, Luis M. A. Bettencourt
2014 The Pre-History of Urban Scaling. *PLoS One*. 9(2).

Parmesan, C.
1996. Climate and species range. *Nature* 382, pp. 765-766.

Parmesan, C., N. Ryrholm, C. Stefanescu, J. K. Hill, C. D. Thomas, H. Descimon, B. Huntley, L. Kaila, J. Kullberg, T. Tammaru, W. J. Tennent, J.A. Thomas, M. Warren.
1999 Poleward shifts in geographical ranges of butterfly species associated with regional warming. *Nature* 399, pp. 579-583.

Pauketat, Tim.

2007 *Chiefdoms and Other Archaeological Delusions*. Altamira Press, Lanham, MD.

Pepper, George H.
1909 The Exploration of a Burial-Room in Pueblo Bonito, New Mexico. In *Putnam Anniversary Volume: Anthropological Essays Presented to Frederic Ward Putnam in Honor of His Seventieth Birthday, April 16, 1909, by His Friends and Associates*, pp. 196–252. G. E. Stechert & Co., New York.

Peregrine, Peter
1991 A graph-theoretic approach to the evolution of Cahokia. *American Antiquity* 56:66–75.

Plog, Stephen and Carrie Heitman
2010 Hierarchy and social inequality in the American Southwest, A.D. 800-1200. *Proceedings of the National Academy of Sciences* 107:19619-19626.

Powers, Robert P., William B. Gillespie, and Stephen H. Lekson
1983 *The Outlier Survey: A Regional View of Settlement in the San Juan Basin.* Reports of the Chaco Center 3. NPS, USDI, Albuquerque.

Py, Michel.
1990 *Culture, Économie Et Société Protohistoriques Dans La Région Nimoise.* Rome : École Française de Rome. Publications de l'École française de Rome (131).
2012 Les Gaulois du Midi, de la fin de l'Age du Bronze à la conquête romaine, nouvelle édition revue et augmentée, collection Les Hespérides, Errance.

R Core Team
2013 R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. http://www.R-project.org/.

Ramos-Jiliberto, R., F.S. Valdovinos, J. Arias, C. Alcaraz, and E. García-Bertho
2011 A network-based approach to the analysis of ontogenetic diet shift: an example with the endangered fish Aphanius iberus. *Ecological Complexity* 8:123-129.

Rawlings, T. A., J. C. Driver
2010 Paleodiet of domestic turkey, Shields Pueblo (5MT3807), Colorado: Isotopic analysis and its implications for care of a household domesticate. *Journal of Archaeological Science* (37)10, pp. 2433-2441.

Raynaud, Claude
2000 Territoire et Peuplement en France, de l'Age du Fer au Moyen Age. L'archéologie spatiale à la croisée des chemins. *The Future of Surface Artefact Survey in Europe*, J. Bintliff, M. Kuna and N. Venclová (Eds.). Sheffield Academic Press. pp. 57-72.

Reid, J. J., and S. M. Whittlesey

1990 The complicated and the complex: Observations on the archaeological record of large pueblos. In *Perspectives on Southwestern Prehistor*y, edited by P. E. Minnis and C. L. Redman, pp. 184-195. Westview Press, Boulder.

Reynolds, C. W.
1987 Flocks, Herds, and Schools: A Distributed Behavioral Model, in Computer Graphics, 21(4) (SIGGRAPH '87 Conference Proceedings) pp. 25-34.

Richerson, P. J., and R. Boyd
2005 Not by Genes Alone: How Culture Transformed Human Evolution. University of Chicago Press, Chicago, IL.

Rocks-McQueen, Doug
2015 Agent Based Modelling and the Person, The Computer Applications and Quantitative Methods in Archaeology (CAA) Conference 2014, 22nd-25th April, Paris.

Rohn, A.H.
1963 Prehistoric soil and water conservation on Chapin Mesa, southwestern Colorado, *American Antiquity,* 28(4), pp. 441-455.

Romanuk, T.N., B.E. Beisner, A. Hayward. L.J. Jackson, J.R. Post, and E. McCauley.
2009 Processes governing riverine fish species richness are scale-independent. *Community Ecology* 10:17-24.

Rouillard, Pierre
1991 *Les Grecs et la peninsula ibérique du VIIIe au IVe siècle avant Jésus-Christ.* Broccard, Paris.

Rousseau, Jean-Jacques
1751 A discourse on inequality. Maurice Cranston, trans. New York: Penguin Books, 1984.

Rusch, Hannes
2014 The Two Sides of Warfare: An Extended Model of Altruistic Behavior in Ancestral Human Intergroup Conflict. *Human Nature* 25:350-377.

Ryan, Susan C.
2003 Albert Porter Pueblo, (Site 5MT123), Montezuma County, Colorado, Annual Report Field Season 2003, Crow Canyon Archaeological Center.
2013 Architectural Communities of Practice: Ancestral Pueblo Kiva Production During the Chaco and Post-Chaco Periods in the Northern Southwest. Unpublished Ph.D. dissertation, Department of Anthropology, University of Arizona, Tucson.
2016 Integration and Disintegration: The Role of Kiva Production in Community Formation in the Prehispanic U.S. Southwest. In *Coming Together: Comparative Approaches to Population Aggregation and Early Urbanization*, edited by A. Gyucha. Institute for European and Mediterranean Archaeology, Buffalo (expected 2017).

Schachner, Gregson

2001 Ritual Control and Transformation in Middle-Range Societies: An Example from the American Southwest. *Journal of Anthropological Archaeology* 20(2):168-194.
2010 Corporate Group Formation and Differentiation in Early Puebloan Villages of the American Southwest. *American Antiquity* 75(3):473-496.

Schmitz, O. J., P. A. Hambäck, A. P. Beckerman
2000 Trophic Cascades in Terrestrial Systems: A Review of the Effects of Carnivore Removals on Plants, *The American Naturalist* 155(2), pp. 141-153.

Schoenwetter, A. E., J. Dittert
1968 Ecological interpretation of Anasazi settlement patterns, *Anthropological Archaeology in the Americas*, B. J. Meggers, Ed., pp. 41-66.

Schollmeyer, K. G., J. D. Driver
2012 The Past, Present, and Future of Small Terrestrial Mammals in Human Diets, *Conservation Biology and Applied Zooarchaeology*, Edited by S. Wolverton and R. L. Lyman, pp. 179-207. The University of Arizona Press, Tucson, AZ.

Schwindt, Dylan M., R. Kyle Bocinsky, Scott G. Ortman, Donna M. Glowacki, Mark D. Varien, and Timothy A. Kohler
2016 The Social Consequences of Climate Change in the Central Mesa Verde Region. *American Antiquity* 81:74-96.

Service, E.
1962 Primitive Social Organization. New York: Random House.

Shanks, Michael and Christopher Tilley.
1991 Social Theory and Archaeology. Polity, Cambridge, U.K.

Shelford, V.
1913 Animal Communities in Temperate America as Illustrated in the Chicago Region. University of Chicago Press. Chicago, Illinois.

Srinivasan, U. T., J. A. Dunne, J. Harte, N. D. Martinez
2007 Response of complex food webs to realistic extinction sequences *Ecology,* 88, pp. 95–114.

Staddon, J.E.R.
1983 Foraging and behavioral ecology, *Adaptive Behavior and Learning*. First Edition, Cambridge University Press, Cambridge U.K.

Steponaitis, Vincas P.
1981 Settlement Hierarchies and Political Complexity in Nonmarket Societies: The Formative Period of the Valley of Mexico. *American Anthropologist,* 83(2):320-363.

Steward, Julian
1955 Theory of Culture Change: The Methodology of Multilinear Evolution.

Urbana, Il.

Stouffer, D. B., J. Camacho, R. Guimera, C. A. Ng, L. A. N. Amaral
2005 Quantitative patterns in the structure of model and empirical food webs. *Ecology,* 86, pp. 1301–1311.

Strabo
1923. *Geography, Volume II, Books 305.* Translated by H. L. Jones. Loeb Classical Library. Harvard University Press, Cambridge, MA.

Strong, William D.
1935 An Introduction to Nebraska Archaeology. The Smithsonian Institution, Washington, D.C.

Summerhayes, VS; Elton, CS
1923 Contributions to the Ecology of Spitsbergen and Bear Island. *Journal of Ecology* 11: 214–286.

Surovell, Todd A., Brigid S. Grund
2012 The associational critique of quaternary overkill and why it's largely irrelevant to the extinction debate. *American Antiquity* 77(4), pp. 672-687.

Tamm, E., T. Kivisild, M. Reidla, M. Metspalu, D. Glenn Smith, C. J. Mulligan, C. M. Bravi, O. Rickards, C. Martinez-Labarga, E. K. Khusnutdinova, S. A. Fedorova, M. V. Golubenko, V. A. Stepanov, M. A. Gubina, S. I. Zhadanov, L. P. Ossipova, L. Damba, M. I. Voevoda, J. E. Dipierri, R. Villems, R. S. Malhi
2007 Beringian standstill and spread of Native American founders, *PLoS ONE*, DOI: 10.1371/journal.pone.0000829.

Tecchioa, S., M. Coll, V. Christensen, J. B. Company, E. Ramírez-Llodra, F. Sardà
2013 Food web structure and vulnerability of a deep-sea ecosystem in the NW Mediterranean Sea, *Deep Sea Research Part I: Oceanographic Research Papers,* 75, pp. 1–15.

Trigger, B.
2006 A History of Archaeological Thought (2nd ed.). Cambridge University Press.

Truett, J.
1996 Bison and elk in the American Southwest: In search of the pristine, *Environmental Management,* 20, pp. 195-206.

Turchin, Peter
2003 Historical dynamics: why states rise and fall. Princeton University Press, Princeton, NJ.

Turchin, Peter, and Sergey Gavrilets
2009 Evolution of Complex Hierarchical Societies. *Social History and Evolution* 8(2):167-198.

Twede, Diana
2002 Commercial Amphoras: The Earliest Consumer Packages? *Journal of Macromarketing* 22(1) pp. 98-108.

Urban, M. C.
2015 Accelerating extinction risk from climate change, *Science,* 348(6234), pp. 571-573.

USGS
2016 Navajo Land Use Planning Project. http://geomaps.wr.usgs.gov/navajo/4corners/index.html.

Vallat, Pierre and Manon Cabanis
2009 Le site de "Champ Chalatras" aux Martres-d'Artière (Puy-de-Dôme) et les premiers témoins archéologiques de la viticulture gallo-romaine dans le bassin de Clermont-Ferrand (Auvergne). Revue Archéologique du centre de la France.

Van der Leeuw, Sander, François Favory, Jean-Luc Fiches
2003 *Archéologie et systèmes socio-environnementaux. Études multiscalaires sur la vallée de Rhône dans le programme Archaeomedes*, Paris, CNRS Éditions, coll. CRA—Monographies 27.

Van der Leeuw, Sander, and James McGlade (Eds.)
1997 *Archaeology : Time, procès and structural transformations.* London : Routledge.

Van Dyke, R. M.
2007a Great Kivas in Time, Space, and Society. In T*he Architecture of Chaco Canyon, New Mexico,* edited by Stephen H. Lekson, pp 93-126. University of Utah Press, Salt Lake City.
2007b *The Chaco Experience: Landscape and Ideology at the Center Place*. SAR Press, Santa Fe.

Van Dyke, Ruth M., R. Kyle Bocinsky, Tucker Robinson, and Tom C. Windes
2016 Great Houses, Shrines, and High Places: Intervisibility in the Chacoan World. *American Antiquity,* 81(2):205-230.

Varien, Mark D.
1999 Sedentism and Mobility in a Social Landscape: Mesa Verde and Beyond. The University of Arizona Press, Tucson, AZ.
2010 Depopulation of the northern San Juan region: Historical review and archaeological context, *Leaving Mesa Verde: Peril and Change in the Thirteenth Century Southwest*, edited by T. A. Kohler, M. D. Varien, A. M. Wright, Eds., Amerind Foundation and the University of Arizona Press, Tucson, AZ, pp. 1-33

Varien, Mark D., Scott G. Ortman, Timothy A. Kohler, Donna M. Glowacki, and C. David Johnson
2007 Historical Ecology in the Mesa Verde Region: Results From The Village Project. *American Antiquity* 72:273-299.

Villard, François

1960 La Céramique Grecque de Marseille (VI[e]-IV[e] siècle). Essai D'histoire économique. Thèse pour le doctorat ès lettres, présentée à la faculté des lettres de l'université de Paris. Editions e. de Boccard. Paris, France.

Vivian, Gordon, and Paul Reiter
1965 *The Great Kivas of Chaco Canyon and Their Relationships*. Monograph 22, School of American Research. University of New Mexico Press, Albuquerque.

Wan, S., D. Hui, Y. Luo
2001 Fire effects on nitrogen pools and dynamics in terrestrial ecosystems: a meta-analysis. Ecological Applications, 11, 1349–1365.

Wardle, D. A.
2011 Terrestrial ecosystem responses to species gains and losses, *Science*332 pp. 1273 .

Ware, John A.
2014 A Pueblo Social History: Kinship, Sodality, and Community in the Northern Southwest. School for Advanced Research Press, Santa Fe, NM.

Wasserman, S., & Faust, K.
1994 Social network analysis: methods and applications. Cambridge: Cambridge University Press.

Watson, Patty Jo
2008 Processualism and After. In Handbook of Archaeological Theories. Edited by R. Alexander Bentley, Herbert D.G. Maschner and Christopher Chippendale, pp. 29-38. Alta Mira Press, Lanham, MD.

White, K. D.
1970. *Roman Farming*. Cornell University Press, Ithaca, NY.

White, Leslie
1949 The Science of Culture: A Study of Man and Civilization. Grove Press, New York.

Wilensky, U.
1999 NetLogo. http://ccl.northwestern.edu/netlogo/. Center for Connected Learning and Computer-Based Modeling, Northwestern University. Evanston, IL.
2005 NetLogo Wolf Sheep Predation (Docked Hybrid) model. http://ccl.northwestern.edu/netlogo/models/WolfSheepPredation(DockedHybrid). Center for Connected Learning and Computer-Based Modeling, Northwestern University, Evanston, IL.

Wilkinson, T. J., J. H. Christiansen, J. Ur, M. Widell, and M. Altweel
2007 Urbanization within a Dynamic Environment: Modeling Bronze Age Communities in Upper Mesopotamia. *American Anthropologist* 109:52-68. DOI: 10.1525/aa.2007.109.1.52

Willey, Gordon R., and Philip Phillips.
1958 *Method and Theory in American Archaeology*. University of Chicago Press, Chicago, IL.

Williams, R. J.
2010. *Network3D Software*. Microsoft Research, Cambridge, UK.

Williams, R. J., E. L. Berlow, J. A. Dunne, A.L. Barabasi, N. D. Martinez
2002 Two degrees of separation in complex food webs, *Proc Natl Acad Sci USA*99, pp. 12913–12916.

Williams, R. J., N. D. Martinez
2004 Limits to trophic levels and omnivory in complex food web: Theory and data. *The Americal Naturalist,* 163, pp. 458-468.

Wilshusen, Richard H., Melissa J. Churchill, and James M. Potter
1997 Prehistoric Reservoirs and Water Basins in the Mesa Verde Region: Intensification of Water Collection Strategies during the Great Pueblo Period. *American Antiquity* 62:664-681.

Wilson, D. S.
2002 Darwin's Cathedral: Evolution, Religion, and The Nature of Society. University of Chicago Press, Chicago, IL.

Wilson, D. S., Wilson, E. O.
2008 Evolution 'for the good of the group'. *American Scientist* 96 (5): 380–389.

Windes, Thomas C.
1987 *Investigations at the Pueblo Alto Complex, Chaco Canyon, New Mexico, 1975- 1979. Vol II, Part 2*. Publications in Archeology 18F, Chaco Canyon Studies. National Park Service, Santa Fe.

Windes, Thomas C.
2015 The Chacoan Court Kiva. *Kiva* 79:337-379.

Windes, Thomas C., and Eileen Bacha
2008 Differential Wood Use at Salmon Ruin, *In Chaco's Northern Prodigies: Salmon, Aztec, and the Ascendancy of the Middle San Juan Region after A.D. 1100,* edited by Paul F. Reed, pp. 113-139. The University of Utah Press, Salt Lake City.

Witt, K. E. K. Judd, A. Kitchen, C. Grier, T. A. Kohler, S. G. Ortman, B. M. Kemp, R. S. Malhi
2015 DNA analysis of ancient dogs of the Americas: Identifying possible founding haplotypes and reconstructing population histories, *Journal of Human Evolution 79,* pp. 105-118.

Wodzicki, K. A.

1950 *Introduced mammals of New Zealand*, (An ecological and economic survey. Bulletin, Department of Scientific & Industrial Research 1950 No. 98, 1950).

Wood, Ellen M.
1983 Agriculture and Slavery in Classical Athens. *American Journal of Ancient History* 8(1):1-47.

Yeakel, J. D., M. M. Pires, L. Rudolfe, N. J. Dominy, P. L. Koch, P. R. Guimarães Jr., T. Grosse
2014 Collapse of an ecological network in Ancient Egypt, *Proceedings of the National Academy of Sciences*, 111, 40, pp. 14472-14477.

Yodzis P, Innes S
1992 Body size and consumer-resource dynamics. *American Naturalist* 139:1151–117.

Yodzis, P., K. O. Winemiller
1990. In search of operational trophospecies in a tropical aquatic food web, *Oikos* 87 pp. 327-340.

Yoon, I., R.J. Williams, E. Levine, S. Yoon, J.A. Dunne, and N.D. Martinez
2004 Webs on the Web (WoW): 3D visualization of ecological networks on the WWW for collaborative research and education, *Proceedings of the IS&T/SPIE Symposium on Electronic Imaging, Visualization and Data Analysis,* 5295, pp. 124-132.

Zhou, W.-X., D. Sornette, R. A. Hill, and R. I. M. Dunbar
2005 Discrete Hierarchical Organisation of Social Group Sizes. *Proceedings of the Royal Society, London*, 272:439-444

TRADE, TERRITORIALITY, ALLIANCES AND CONFLICT : COMPLEXITY SCIENCE APPROACHES TO THE ARCHAEOLOGICAL RECORD OF THE U.S. SOUTHWEST WITH A CASE STUDY FROM LANGUEDOC, FRANCE

ECHANGES, TERRITORIALITÉ, ALLIANCE ET CONFLIT : APPROCHE PAR LES SCIENCES DE LA COMPLEXITÉ DES DONNÉES ARCHÉOLOGIQUES DU SUD-OUEST DES ETATS-UNIS ET D'UNE ÉTUDE DE CAS EN LANGUEDOC (FRANCE)

Abstract

This project utilizes network analysis and agent-based modeling to examine long-standing questions that can only now be asked with the rich data provided in southwestern Colorado and southern France: how Gauls and colonists established economic partnerships, how violence may have shaped the development of multiple levels of leadership, and how early farmers interacted with their environments. Writing a dissertation composed of three distinct case studies, two from the U.S. Southwest and one from the south of France, I use tools developed in complexity science to better address how people in the past dealt with challenges related to resource acquisition. Agent-based modeling and network analysis (both social network analysis and trophic network analysis) will allow me to characterize human decision-making processes and discuss how sharing of strategies within a group can lead to greater fitness of those in the in-group.

Abstrait

Ce projet utilise l'analyse de réseaux et la modélisation à base d'agents pour examiner des sujets classiquement traités mais qui peuvent maintenant être abordés, grâce aux riches données rencontrées dans le sud-ouest du Colorado et en France méridionale : comment les Gaules et les marchands méditerranéens établissaient leurs partenariats économiques, comment la violence a pu façonner le développement de niveaux divers de leadership, et comment les premiers agriculteurs interagissaient avec leur environnement. Pour écrire cette thèse composée de trois études de cas différents, deux dans le Sud-Ouest des États-Unis et un en France méridionale, nous utilisons des outils élaborés par les sciences de la complexité pour mieux aborder comment les individus de la préhistoire surmontaient les défis liés à l'acquisition de ressources. La modélisation à base d'agents et l'analyse de réseaux (sociaux et trophiques) nous permettront de décrire les processus décisionnels et d'analyser comment le partage de stratégies au sein du groupe peut entraîner une plus grande aptitude des individus à agir au sein du groupe.

by Stefani Allison Crabtree, Ph.D.
Washington State University &
Université de Franche-Comté

Co-chairs: Timothy A. Kohler & François Favory