A GIS approach to landscape scale archaeoacoustics

Kristy Elizabeth Primeau
University at Albany, State University of New York, keprimeau@gmail.com

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A GIS APPROACH TO LANDSCAPE SCALE ARCHAEOACOUSTICS

By: Kristy. E. Primeau

A Dissertation
Submitted to the University at Albany,
State University of New York
in Partial Fulfillment of the Requirements for the Degree of Doctor of Philosophy

College of Arts & Sciences
Department of Anthropology
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Abstract

This research presents the development and critical assessment of an Archaeoacoustics Toolbox for Geographic Information Systems (GIS) technology written in the Python programming language, and applies this methodology to cross cultural case studies exploring the importance of soundsheds in an anthropological-archaeological context. As counterpoint to a common critique of experiential theoretical approaches the Soundshed Analysis and Soundshed Analysis-Variable Cover tools provide a replicable means of modeling baseline estimates of the experience of sound. Testing against modern acoustical studies establishing scientific accuracy, and explanations of the sound physics calculations performed by the tools are provided. The tools are then applied to case studies situated in Ancestral Puebloan sites within Chaco Canyon; the Classic Period Maya Kingdom of Copan; and nineteenth- and early twentieth-century Ireland to explore a variety of modeling techniques and culturally-derived inputs. In addition to demonstrating the use of the Archaeoacoustics Toolbox, each of the case studies represents an individual contribution to understanding the importance of what was heard in the past. By incorporating a consideration of landscape acoustics, archaeologists can more fully understand the embodied experience explored through phenomenological, perceptive, and performance-based approaches. A GIS approach to landscape scale archaeoacoustics provides a contextualizing framework by which researchers can approach auditory hypotheses, explore embodied experience, and listen to what the past is telling us.
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Preface: Previous Publications

This dissertation includes material from several previously published works. Permission from the respective publishers to include these materials can be found in Appendix H. All of the publications have been coauthored by one or more individuals and, therefore, no publication has been reproduced in its entirety. Portions of the materials appearing herein in their published wording reflect my original work¹. Ideas and written sections of the publications which reflected purely combined authorship (myself and others) have been removed or revised to reflect only original contributions. Research performed or sections of the publications written by one or more of my coauthors are cited as appropriate when it was essential to maintain this information as part of the case study. The articles listed below are being included because they were part of the programmatic line of research that comprised my dissertation and including them provides a coherent and appropriately sequenced investigation documenting the development and application of the Archaeoacoustics Toolbox. Except as noted, all images associated with the previous publications listed below that are presented in this dissertation represent original work.

The publications are as follows:

¹ Note that in all instances my original work was subject to editing as a result of the peer reviewed publication process, therefore, it may include minor grammatical and stylistic changes as proposed by respective co-authors and publication editors. Ideas and content remain my own.

ix
Primeau and Witt 2018
Primeau, Kristy E., and David E. Witt

2018 Soundscapes in the Past: Investigating Sound at the Landscape Level.

Summary of Use in Dissertation: This was the initial publication reporting the functionality, design, and testing of the Soundshed Analysis Tool. Excerpts and concepts from this publication appear throughout the dissertation as follows:

- Chapter 4
  - Equations 5, 7, and 8 appeared in Appendix A of Primeau and Witt 2018
  - Acoustic Science Section text, page 92
  - Psychoacoustics Section text, pages 109-111

- Chapter 5
  - Text, pages 133-137
  - Table 5.2 is based on Primeau and Witt 2018 Table 1
  - Figure 5.2 appeared in Primeau and Witt 2018 as Figure 1
  - Table 5.3 appeared in Primeau and Witt 2018 as Table 2
  - Figure 5.3 appeared in Primeau and Witt 2018 as Figure 2

- Chapter 7:
  - Introduction text, pages 158-9
  - Methods of Investigation Section, pages 163-165, 168-176
  - Figure 7.2 appeared in Primeau and Witt 2018 as Figure 3
  - Figure 7.4 appeared in Primeau and Witt 2018 as Figure 4
  - Figure 7.5 appeared in Primeau and Witt 2018 as Figure 5
Methods of Investigation Section text, pages 173, 176

Figure 7.7 appeared in Primeau and Witt 2018 as Figure 7

Model Assumptions text, page 183

- Chapter 10:
  - Introduction text, page 256

Authorship: The following sections of Primeau and Witt 2018 represent original authorship: 2. Theory, 2.1 Hearing – the perception of sound, 3. Method, 3.1 Tool Validation, Appendix A, and all tables and figures. The remainder of the sections represent combined authorship.

Witt and Primeau 2019

Witt, David E., and Kristy E. Primeau

2019 Performance Space, Political Theater, and Audibility in Downtown Chaco.


Summary of Use in Dissertation: This publication provided further interpretation of the Chacoan Case Study. Limited excerpts and concepts from this publication appear in the dissertation as follows:

- Chapter 7:
  - Figure 7.1 appeared in Witt and Primeau 2019 as Figure 1
  - Introduction text, page 159
  - Methods of Investigation Section text, pages 171-173
  - Figure 7.6 is based on Witt and Primeau 2019 Figure 4
Authorship: The following sections represent original authorship: 2. Modeling Methods, 2.1 Modeling Inputs, 2.2 Modeling Steps, Figure 4, and Figure 5. Remaining sections, figures, and tables represent combined authorship. As described in Witt and Primeau (2019:9), “Individual author contributions are as follows: conceptualization, D.E.W.; methodology, D.E.W., K.E.P.; software, K.E.P.; writing—original draft preparation, D.E.W., K.E.P.; writing—review and editing, D.E.W., K.E.P.; visualization, K.E.P.”

Richards-Rissetto et al., n.d.
Richards-Rissetto, Heather, Kristy E. Primeau, David E. Witt, and Graham Goodwin

Summary of Use in Dissertation: This is the initial publication reporting the functionality, of the Soundshed Analysis – Variable Cover Tool, although its development is also discussed in several unpublished works (Goodwin et al. 2018a, 2018b; Primeau 2019). It also represents the use of a reconstructed elevation model “Urban DEM” in modeling courtesy of Heather Richards-Rissetto (2010). Limited excerpts and concepts from this publication appear in the dissertation as follows:

• Chapter 6:
  o Introduction text, pages 138-139
- Soundshed Analysis – Variable Cover Tool Development text, pages 139-141

Chapter 8:
- Methods of Investigation Section text, page 194
- *Kahkab* and Ritual Practice in Suburban Copán Section text, pages 211-212
- Methods of Investigation: Scenario 3 Section text, pages 212-213
- Vegetation Reconstruction and Modeling text, pages 213-218
- Figures 8.17 and 8.18 appear together in Richards-Rissetto et al., n.d. as Figure 5
- Figure 8.19 appears in Richards-Rissetto et al., n.d. as Figure 6
- Figure 8.20 appears in Richards-Rissetto et al., n.d. as Figure 7
- VR Integration Section text, page 219
- Discussion and Future Directions Section text, page 220

Appendix G:
- Soundshed Analysis – Variable Cover Tool Section text, pages 11-12

Authorship: The following sections of this publication represent original authorship: Soundshed Analysis Toolbox, Project Specific Environmental Inputs, GIS Results and Interpretation, Table 1, and Figures 5-8. The remainder of the publication represents combined authorship.
Primeau et al., n.d.
Primeau, Kristy E., Jennifer Shaffer Foster, and David E. Witt


Summary of Use in Dissertation: This publication provides contrast to previous applications of the Soundshed Analysis Tool by exploring contained rather than intentionally projected sounds in a quotidian historic context. This study also represents the first use of a Digital Surface Model in producing estimated soundsheds. Excerpts and concepts from this paper appear throughout the dissertation as follows:

- Chapter 4
  - Archaeoacoustics and Cultural Anthropology of Sound text, page 120

- Chapter 9
  - Introduction text, page 221
  - From Raths to Cillíní Section text, pages 221-2, 224-5
  - Cillíní in the Irish Cultural Landscape and Ethnographic Record section text, pages 226-228
  - The Acoustic Environment of Headford, County Galway Section text, pages 228-231
  - Methods of Investigation Section text, pages 231-248
  - Figure 9.1 appears in Primeau et al., n.d. as Figure 1
o Figure 9.2 appears in Primeau et al., n.d. as Figure 2

o Figure 9.4 appears in Primeau et al., n.d. as Figure 3

o Figure 9.6 appears in Primeau et al., n.d. as Figure 4. This image is published at:

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o Figure 9.7 appears in Primeau et al., n.d. as Figure 5

o Figure 9.8 appears in Primeau et al., n.d. as Figure 6. This image is published at:

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o Figure 9.9 appears in Primeau et al., n.d. as Figure 7. This image is published at:

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o Figure 9.10 appears in Primeau et al., n.d., as Figure 8

o Review and Discussion Section text, pages 248-252
Reflection and Conclusion Section text, pages 252-255

Authorship: The following sections of the publication represent original authorship:
Landscape Phenomenology and Anthropology of the Senses, Modeling the Spread of Sound in the Landscape, and Places within Headford’s Landscape. The remainder of the publication represents combined authorship. As noted above, Figures 5-7 are used for educational purposes courtesy of the National Inventory of Architectural Heritage and are copyright of the Department of Housing, Local Government and Heritage. The remainder of the figures and tables appearing in this publication represent original work.
Chapter 1. Introduction

This research presents the development and critical assessment of an archaeoacoustics toolbox for Geographic Information Systems (GIS) technology using the Python programming language. The sound physics calculations performed by the model have been tested against established acoustical studies of modern sound-producing scenarios for scientific accuracy, and were then applied to a number of case studies from cross cultural contexts to explore a variety of modeling techniques and culturally-derived inputs. The development of this tool provides a replicable methodology for establishing baseline estimates of the experience of sound. By incorporating a consideration of landscape acoustics, archaeologists can more fully understand the embodied experience explored through phenomenological, perceptive, and performance-based approaches.

The Experience of Sound

Sound “is essential to our lived-in world, for communication and allowing us to identify place” (Cummings and Whittle 2004:8).

In recent years, archaeological research has trended towards the exploration of the experiences of past people, seeking new methodologies and incorporating reconstructions to develop this understanding. However, these studies have primarily consisted of viewshed models or visibility analyses (e.g., Carlson and Jordan 2013; Chapman 2003; Cummings 2003; Cummings and Whittle 2003; Fisher et al. 1997;
Fitzjohn 2007; Gaffney et al. 1996; Llobera 1996; Llobera 2007a; Llobera 2007b; Maschner 1996; Pollard and Gillings 1998; Rennell 2012; Tilley 2008; Van Dyke et al. 2016) and descriptions of movement within and between sites (Carballo and Pluckhahn 2007; Eve 2012; Llobera 2000; Lock and Pouncett 2010; Tilley 1994). The few studies that acknowledged the importance of what was heard in the past stated that they lacked the tools and/or methodology to further pursue the topic (Constantinidis 2004; Frieman and Gillings 2007; Mlekuz 2004; Tilley 2008). Their discussion was primarily limited to auditory experience at a theoretical level, or as experienced within individual sites or features (e.g., Azevedo et al. 2013; Cross et al. 2002; Cross and Watson 2006; d'Errico and Lawson 2006; Devereux 2002; Eneix 2014; Iannace et al. 2010; Iannace et al. 2014; Jahn et al. 1996; Jimenez et al. 2013; Kolar 2013, 2017; Markham et al. 2013; Reznikoff 2008; Scarre 2006; Wall 2018; Watson and Keating 1999).

Phenomenological studies of “acoustic archaeology” or “archaeoacoustics,” have provided the greatest methodological advances to date (Boren 2016; Díaz-Andreu and García Benito 2012; Liwosz 2018; Mattioli et al. 2017), nevertheless practical application of these methodologies at the landscape level has been limited - primarily gaining momentum within the past five years (Díaz-Andreu et al. 2017; Mattioli and Díaz-Andreu 2017; Mileson 2018; Mlekuz 2004; Van Dyke and de Smet 2018). Phenomenological theory offers a structure for the exploration of “soundscapes,” defined by the International Organization for Standardization as the “acoustic environment as perceived or experienced and/or understood by a person or people, in context (ISO 2014:1; e.g., Scullin and Boyd 2014; Miller 2008; Pijanowski et al. 2011; Villanueva-Rivera et al. 2016).
2011).” However, as the paradigm of phenomenology is subject-centered or experience based, it is not the only theoretical paradigm which can be applied to the importance of sound in archaeological study as will be described.

This research concentrates on the importance of sound within the landscape. It begins with the development of a Soundshead Analysis tool to model soundscapes, and focuses on the way that sound spreads through the natural and built environment, under a variety of atmospheric and environmental conditions. Next, it presents case studies in the application of archaeoacoustics. Input data applied to the case studies is in part derived from the literature (e.g., site locations, osteological data), with additional data (e.g., climatological information) derived from modern correlates or measurements. Instructional materials have been developed in preparation for distribution of this open-source code for use by other researchers.

**Analytical Innovation**

The Soundshead Analysis Tool is based on a Microsoft Excel spreadsheet created by David Witt to study sound profiles over straight line paths, and on SPreAD, or “the System for the Prediction of Acoustic Detectability” developed by the US Forest Service (Harrison et al. 1980). SPreAD-GIS, an initial computerized version of SPreAD, was adapted for use in GIS by Sarah Reed in 2009 (Reed et al. 2009, 2010) and has been further modified to form the basis of the Soundshead Analysis Tool and the Variable Cover tool. These are the first of several modeling tools proposed for the Archaeoacoustics Toolbox. The Soundshead Analysis Tool beta version (0.9.3) was written in the Python
programming language for 32-bit ArcGIS 10.3.

The tools developed for the Archaeoacoustics Toolbox bridge what have traditionally been viewed as two very different practices: phenomenological inquiry and computer assisted modeling. Phenomenological approaches have been critiqued for lacking replicable methodology (e.g., Cummings and Whittle 2004; Hamilton et al. 2006; Johnson 2012; Rennell 2012), while many leading phenomenologists simultaneously denounce computer based modeling methods as positivistic (e.g., Hacigüzeller 2012; Sui 1994; Tilley 2010:25-26). As an answer to the critiques of both sides, this research illustrates how GIS technology can be utilized to investigate soundscapes empirically, providing a replicable methodology for establishing the baseline data for the experience of sound. It is important to note that allowing all researchers a shared baseline or starting point from which to draw their hypotheses does not in itself preclude the application of experiential fieldwork methodologies, a cornerstone of phenomenology and other subject-based survey methods. In fact, fieldwork should be conducted whenever possible to further investigate claims of audibility and add observational data to the record.

Dedicated sound prediction and modeling software is commercially available, however, modeling the spread of sound in a GIS environment places an emphasis on the spatial location and extent of the soundshed, rather than a detailed acoustical reconstruction. This allows us to incorporate acoustics into analyses of relationships between sites and features within the landscape, and study the cultural implications of those relationships. While noise analysis software can be cost-prohibitive or otherwise
inaccessible to archaeologists, GIS is a prevalently used tool that most archaeologists can access and operate, making it an ideal candidate for enrichment.

**Layout of Dissertation**

The goals of this research are to develop an archaeoacoustics analysis toolbox for Geographic Information Systems (GIS) and to apply archaeoacoustical methodology using existing geospatial data from a variety of archaeological contexts and cultures to create a series of GIS-based estimated “soundshed” images. The cultural significance of the experience of sound is discussed in relation to each of the case studies. In sum, this study posits: *Given the continuity of the physical laws governing sound over time and current advances in computer programming and Geographic Information Systems (GIS), can a methodology be established for modeling the spread of sound throughout landscapes and exploring the importance of these soundsheds in an anthropological-archaeological context?*

To satisfy the objectives briefly outlined above, this study was completed in four phases:

**Phase 1: Background Research**

This dissertation begins with a review of important contributions to archaeoacoustics, relevant theoretical perspectives, and basic sound physics. Each of these subjects was influential in the development of a Soundshed Analysis tool. In Chapter 2 I review many significant contributions to archaeoacoustics, archaeomusicology, psychoacoustics, and soundscape archaeology. This review not only
emphasizes the field’s interest in a GIS-based solution to sound mapping, but supports
the incorporation of an interdisciplinary acoustical science approach. As a result of this
work, I recommend an anthropological/archaeology approach be utilized to situate the
results of soundshed modeling within appropriate perceptual and cultural perspectives; a
conclusion which I echo in the next chapter. In Chapter 3 I review the trends in
archaeological theory which have both supported and critiqued the use of GIS
methodologies in relation to sensory archaeology and subject centered survey. After a
review I provide a more detailed focus on the theoretical perspectives applied within the
case studies appearing in later chapters and the types of hypotheses that these
perspectives are suited to address. Chapter 4 presents a primer on sound physics,
reviewing basic concepts with which many archaeologists may be unfamiliar. In addition,
this chapter introduces acoustical standards which are well known to the acoustic science
community and should be reviewed by archaeologists seeking to study sound. Many of
the concepts and formulae presented within this chapter form the basis for calculations
performed by the Soundshed Analysis Tool.

Phase 2: Tool Development, Validation, and Toolbox Expansion

Chapter 5 describes the preliminary tool development phase, and applicable
acoustic formulae/ sound physics calculations performed by the tool. The choice of
Python scripting for GIS modeling purposes is also discussed. After development the
initial soundshed modeling tool was then tested against established acoustical studies of
modern sound-producing scenarios to establish scientific accuracy. Chapter 6 describes
an expansion of the Soundshed Analysis Toolbox. Inspired by the need to address a variety of modeling conditions, variations on modeling inputs and study applicability led to the development of a second tool using the Soundshed Analysis tool as a template. The Soundshed Analysis – Variable Cover tool’s development is discussed in this chapter.

**Phase 3: Cross-Cultural Application**

The application of the Archaeoacoustics Toolbox to case studies demonstrates how its tools can be used to incorporate a consideration of sound in archaeological research. These chapters all share some common features. At a basic level, unique environmental, climatological, and ecological factors pertaining to each location impact the ability of sound to travel throughout the landscape and require the user to choose from among the available tools to appropriately model the spread of sound in a given location. The sound source, such as the use of the human voice or particular instruments important to that culture will also account for variations between case studies. In some cases, it may be that silence rather than volume is desired. This relates to the intention of those producing the sound and the context of the sound production (e.g., ritual/ceremonial or socio-political contexts). Therefore, each case study is placed within an appropriate cultural context and includes ethnographic accounts wherever possible.

Chapter 7 investigates Ancestral Puebloan sites located in Chaco Canyon, NM dating from c. 850-1140 CE. Chacoan asymmetrical power relations and emphasis on ritual performance naturally lend these locations to acoustic study. Chapter 8 takes us to
Ancient Maya sites located in Copán, Honduras dating from the reign of Ruler 13 (c. 695 CE) through the reign of Ruler 16 (c. 810 CE). This case study also makes use of the Variable Cover tool, highlighting the different tool applications between study locations within the urban core and the hillside maize production communities. Finally, Chapter 9 considers reuse of Early Medieval sites located in County Galway, Ireland during the nineteenth and early twentieth centuries CE. Here liminality and the edge of perceptions blend with colonial influence, familial identity, and folk memory.

**Phase 4: Discussion and Tool Distribution**

Chapter 10 and associated appendices discuss the intent to release the Archaeoacoustics Toolbox as an open source tool for distribution to other researchers at the conclusion of this project. Appendices provide instructional materials (i.e., user guides) and scripts to accompany the Toolbox.

**Assumptions and Limitations**

This analysis utilizes modeling inputs primarily derived from literature studies, such as the dominant frequency (in Hz) of culturally produced sounds, sound pressure levels (in decibels or A-weighted decibels), and other inputs. In the majority of cases, the analysis also uses historical climatological data to derive model inputs. The consideration of these and other input based biases are discussed primarily within the context of their appropriate case studies. Additionally, the use of modern LIDAR or elevation datasets may skew modeling results; modern features, such as roads or buildings, could affect how sound spreads throughout the landscape. Efforts have been made to identify and...
use reconstructed elevation datasets whenever possible. Finally, limitations are expected to be inherent within the various soundshed modeling tools, including certain complexities of sound physics that are difficult to model in GIS, such as canyon effects and reverberation. These limitations identified during the creation of the Soundshed Analysis Tool are discussed in respect to its methodology and development. Future analyses by other researchers applying tools within the Archaeoacoustics Toolbox to their own studies would primarily be impacted by the modeling input assumptions listed above.

**Significance and Impacts**

This research will result in the creation, application, and distribution of a methodological advancement in archaeological inquiry. Recent trends in archaeological studies have focused on experiential understandings of the past, and the mediation of the senses in individual and group identity formation, structures of power, and landscape organization. However, until the last decade an understanding of the sonorous environment has comprised only a small part of this work. The Soundshed Analysis Tool and Archaeoacoustics Toolbox will meaningfully contribute to the future of archaeology by establishing methods to model and explore the spread of sound throughout anthropogenic landscapes. This research also provides an opportunity to expand the methodologies used in phenomenology, a theoretical approach which has critiqued the use of computer aided inquiry, while lacking the methodological balance of empirical study. Finally, in addition to demonstrating the use of tools within the Archaeoacoustics Toolbox and the theories applicable to archaeoacoustics, each of the case studies represents an individual contribution to our understanding of the importance of what was
heard in the past. A GIS approach to landscape scale archaeoacoustics provides a contextualizing framework by which researchers can approach auditory hypotheses, explore embodied experience, and listen to what the past is telling us.
Within this decade, the field of archaeoacoustics has become increasingly popular as archaeological research has trended towards the exploration of the experiences of past people, particularly through engagement with the senses, seeking innovative methodologies and associated theories to develop this understanding. The merit of these investigations is evident because the phenomena of sounds and auditory experiences occurred ubiquitously throughout time and within all cultures irrespective of individual variation in the types of sounds produced or the meanings attributed to them.

From its inception, archaeoacoustics has been closely tied with standards and methods originating within the field of acoustic science. Current research approaches to archaeoacoustics, psychoacoustics, soundscapes, and archaeomusicology are as multifaceted as the sonic hypotheses that they can explore. In acoustic archaeology, the considerable variation in approaches often derives from how acoustic data is collected or produced. Some of these methods include: subject-centered-survey, on-site experimentation and recording, reproduction or playing of instruments, and computer aided modeling such as Computer Aided Design (CAD), Virtual Reality (VR), or Geographic Information Systems (GIS) approaches.

**Early Archaeoacoustics and Archaeomusicology**

Prior to formal studies in acoustics, archaeologists more often focused on the relationship of acoustical properties to communication and ritual. In 1973 Lynch
questioned whether the blocking of the entrances into Irish passage graves truly represented the final use of the tombs. Although burials ceased to occur once the graves were closed, the entrance chamber to the main mound at Newgrange (Co. Meath) exhibited a 30 cm gap between the roof of the outer passage and that of the inner passage beneath a decorated lintel. This opening was filled with a block of quartz which, along with the surrounding stone, showed evidence that the gap had been repeatedly opened and closed (Lynch 1973:148-9). Lynch compared this site with several other passage graves and found that several could have had similar features. Since the apertures were too small for a person to crawl through, they were not used as entrances; nor was it likely they were used to pass subsequent burials or offerings into the tombs as no material remains were found beneath the openings (Lynch 1973:152). Instead, Lynch proposed that these gaps were used to communicate with the deceased, or as a type of oracle. “People might seek the advice of their ancestors by asking their questions through the slit and their distorted words would come back to them as an answer, of which they could make what they liked (Lynch 1973:152).” Like many archaeoacoustic hypotheses, this appears on the surface to be hard to confirm, as the importance of what was heard does not always leave direct evidence. However, Lynch looked beyond the funeral as the last use of these large structures, which would have taken a long time to construct, towards potential ongoing ceremonial usage and interaction.

In 1983 & 1985 Reznikoff and Dauvois embarked on one of the earliest examples of archaeoacoustic fieldwork. Their study focused on the correlation between sound and the location of rock art within three caves: Portel, Fontanet, and Niaux, located in Ariège,
France (Reznikoff and Dauvois 1988:238). Reznikoff and Dauvois likened the caves to instruments and studied resonance, defined by the authors as “amplification of sound intensity or duration,” by using the human voice to produce a variety of sounds (e.g., a, o, mm, and hm) at various locations and different heights along the cave walls (Reznikoff and Dauvois 1988:239-40). Observation was made by listening (unaided by instrumentation) and resonant locations were mapped. This data was overlaid on the mapped locations of rock art. While one cave, Fontanet, did not experience much variation in sound, three galleries within the Portel cave and one within the Niaux cave exhibited a significant (>80%) correlation between the locations of images and resonant places (Reznikoff and Dauvois 1988:240-1). From their work the authors concluded that “the images are in sonorous places or the immediate vicinity,” that is, images were located on a wall within approximately 1m of the resonant place, and that “the good sound places are image locations (there is an image in the nearest usable location.) In particular, the best sound places are always used or at least marked” (Reznikoff and Dauvois 1988:241).

As archaeoaoustics began to develop, so too did archaeomusicology. The term archaeomusicology was originally used by Lund who systematically studied prehistoric Scandinavian music (or use of artificially made sounds) from the Final Paleolithic period through the Viking period (c.10000 BCE – c.1050 CE) (Lund 1981:246). Importantly, Lund’s definition of music included both musical instruments in the traditional sense, as well as other “sound producing devices” such as rattles attached to wagon straps. Lund’s archaeomusicology combined the Hornbostel-Sachs typological classification system (see Hornbostel and Sachs 1961) with five “probability groupings” for sound producing
devices. This combination was meant to address some of the uncertainty surrounding the identification of sound producing devices within the archaeological record. These probability groupings included: 1. Artifacts that are “clearly sound producing devices”; 2. Artifacts with a “strong potential” (e.g., bones which appear to have “finger holes”) for being sound producing devices; 3. “Probable” sound producing devices with dual functions per ethnographic analogies (e.g., necklaces or clothing embellishments); 4. Artifacts that had a secondary function as sound producing devices but were not created to be instruments (e.g., bangles); and 5. Artifacts with unknown purpose that could be interpreted to produce sounds as a primary or secondary function (Lund 1981:247). By combining probability and typology in this way, Lund provided a framework from which to investigate sound in the material record.

**Technological Advancements in Archaeoacoustics and Archaeomusicology**

By the early 1990’s many researchers began to include the use of technology in their work, to produce, record, and even interpret the acoustic properties of instruments and spaces. Drawing on the earlier work of Reznikoff and Dauvois, Waller (1993a & 1993b) continued to explore the acoustic properties of French upper Paleolithic cave sites containing rock art. Waller focused on the reflection or echoing properties of rock art locations and sought to obtain “…quantitative acoustic measurements that can be objectively analysed [sic] for statistical validity (Waller 1993b:91).” Waller produced sounds using the human voice, clapping, and by “using a spring loaded device designed to deliver a percussive sound with reproducible intensity at a level comparable with natural clapping (Waller 1993b:92).” These sounds were recorded on cassette via an
omnidirectional microphone and analyzed using a calibrated sound level meter. Waller found that rock art locations depicting ungulates were correlated with rock faces where echoes or reverberation were observed, and whereas areas depicting felines were found in areas with low reflectivity or “poor acoustics” (Waller 1993a:501). Sound reflections in these areas could, therefore, have evoked the sound of galloping hooved animals paired with their visual representations or represented the silent stealth of stalking cats (Waller 1993b: 94).

Following in the footsteps of Lynch, Devereux and Jahn (1996; Jahn et al. 1996) performed a resonance study at six prehistoric English and Irish “chambered structures,” including the main mound at Newgrange (Co. Meath), the site discussed in Lynch’s (1973) work. Devereux and Jahn hypothesized that researchers could be informed as to whether vocalizations or music were performed there by determining the acoustical resonance frequency of the internal chamber (1996:665). The equipment used in the study included an “omnidirectional loudspeaker driven by a variable frequency sine-wave oscillator and a 20-W amplifier, with sound frequency verified by an external, hand-held digital multimeter (Jahn et al. 1996:649).” The sound source was typically placed at the center of the chamber, either on the floor elevated with a tripod, and once the dominant resonance frequency was determined, survey was conducted over a grid within the structures to record horizontal standing wave patterns.

In addition to the acoustical survey within the structures, Jahn et al. also attempted to calculate the resonance frequencies mathematically by solving the Helmholtz (reduced wave) equation for acoustic potential using the geometries of the various structures.
These “theoretical predictions” had varying degrees of success, though most of the predicted values came close to the observed acoustic conditions. For all six sites, resonances occurred within the range of the male voice at a frequency of approximately 110 H, therefore, it could be possible that acoustics played an important role in the use, if not design, of these sites (Jahn et al. 1996:652-3, 657-8).

Watson and Keating, largely following the example set by Devereux and Jahn, also studied acoustic reflection, transmission, and standing waves, as well as the impacts of percussive sounds and the potential for Helmholtz Resonance at two sites in northeastern Scotland. Although both monuments are megalithic in nature, Easter Aquorthies, is an open air recumbent stone circle while Camster Round cairn is an enclosed passage grave, therefore, the sites represented two distinct acoustic environments (Watson and Keating 1999). The instrumentation used in the study consisted of a “pink noise” amplifier, omnidirectional microphone, digital tape recorder, and “real time spectrum analyzer” to survey the sites on a 2 meter grid (Watson and Keating 1999:327). Surveys also included the use of scale models, percussive instruments, and listener observations within and outside the sites (Watson and Keating 1999:330-32). Despite their differences, the acoustic phenomena at both sites were shown to be inclusive and exclusive of those within and outside the site boundaries, respectively.

2 ANSI defines “Pink Noise” as: “a noise for which the spectrum density is inversely related to frequency. The slope of the pressure spectrum level of pink noise is minus 3 decibels per octave. In pink noise the energy contained within a proportional frequency band within a specified frequency range is a function solely of the proportionality constant (ANSI S3.20-1973:37).”
At Easter Aquorthies reflection of sound within the stone circle created a higher sound pressure level (SPL) than could be expected in an open area outdoors. This increase in SPL fell away when observed from outside the circle (Watson and Keating 1999:327). At Camster Round where the equipment was placed within the central chamber, the stone walls reflected the sound resulting in amplified echoes. Around the outside perimeter of the cairn, the transmission of sound varied. Furthermore, when standing waves were produced those inside the chamber noticed several effects such as changes in volume and pitch due to movement of themselves or others, and a sensation of not knowing the sound source location. However, while these variations were observed inside, the sound outside the perimeter of the cairn could seem normal (Watson and Keating 1999:328-30). At these megalithic sites, more often studied for their conspicuous visibility, sound was shown to produce a “heightened sense of mystery” contributing to their mystique and creating differences between participants who were permitted access to the sites, and those for whom access was restricted (Watson and Keating 1999:335).

Methodological Advancements in Archaeoacoustics and Archaeomusicology

By the 80’s and 90’s a number of studies, such as those discussed above, had documented and explored acoustic effects, including echoes, resonance, and reverberation, at various sites. In reaction to this, and perhaps fueled by post-processual theories (see Chapter 3) scholars began to delve deeper into the human relationship with acoustic effects while formalizing archaeoacoustical methodologies. In 2006 Watson dedicated a paper to considering intentionality in sound. He posed several questions, including whether the layout of sites, such as Easter Aquorthies, were intentionally
designed for acoustic effects, if these effects were unintentional byproducts, or, as he suggests, these effects were originally unintentional but once noticed subsequently became important during the use of those sites (2006:14). Whereas the modern western conception of intentionality is seen as a binary dichotomy, ethnographic accounts show that other cultures do not necessarily perceive cause and effect as purely deliberate or unintentional, adopting a rather dynamic view of causality. For example, when using an instrument to produce the sound of a god, the performer may become that god. Likewise, an object produced by one culture then circulated into another, may be repurposed to become a sound producing device when this was not its original intended purpose. In this way pottery food vessels could also serve as drums, etc. (Watson 2006:12-14) reminiscent of probability groupings four and five in Lund’s classification system (1974).

To investigate intentionality, Watson repeated the methodologies described above (see Watson and Keating 1999) at Stonehenge. The results of his work showed that standing waves were created within the sarsen circle, causing perceptual effects as described and experienced at Easter Aquorthies and Camster round (see above), along with the amplification of higher frequency sounds. Outside the circle, the large stones attenuated the higher frequency sounds (Watson 2006:18). As correlation does not imply causation (see Waller 1993b:95-98 for related critiques of archaeoacoustics), Watson supplemented acoustical analysis with investigation of the site – determining that “the inner faces of many stones were dressed to be flat or concave, which improves their ability to reflect sound, while their outer surfaces are irregular or even convex (Watson
2006:19).” Ultimately, Watson suggested a reflexive approach, incorporating dynamic multisensory experience with fieldwork, theory, and ethnography.

Building on the concept that acoustic effects, even if unintentional, would have been noticed in the past, Cross and Watson (2006) define several “standard” approaches to investigating the experience of sound in enclosed spaces. These quantifiable attributes of sound correspond to subjective psychological perceptions which more accurately describe how sonic physical processes would have been interpreted in the past (see Chapter 4 for further discussion). Included in the list were: measures of intensity (total sound level), temporal effects (objective clarity, reverberation time), and spatial effects (lateral energy fraction/objective envelopment, total sound level, clarity/reverberation time) (Cross and Watson 2006:109-11). Measurement of one or more of these phenomena has indeed become standard practice in recent archaeoacoustic studies within enclosed spaces, and arguably can be seen in studies which predate these “standards” as well.

To explore the psychoacoustic impacts of sound production Cross and Watson review a case study based on the earlier work of Cross et al. (2002) in which flint knapping was shown to produce flutter echoes, which evoked the perception of hearing a supernatural avian entity (2006:114). The perception of acoustic effects was not evaluated in isolation, however. Exploration of the lithics as ideophones included formalizing the procedures for producing sound (“performance”), categorizing the sounds produced, and performing “use wear” analysis on damage to the blades as a result of sound production (Cross et al. 2002:3). Percussion was shown to create “small densely
clustered surface cones” at the midpoint or distal end of the blade’s ventral surface (Cross et al. 2002:3-6). Having determined that sound could be produced by the blades, and that sound production would leave clear traces, 425 French Upper Paleolithic blades were examined for use wear related to sound production. None of the lithics studied exhibited signs of having been used as ideophones (Cross et al. 2002:6). Although the results in this case were negative, this systematic investigation and conclusion typifies and further supports the use of Watson’s (2006) reflexive approach to archaeoacoustic study.

In a similar study, d’Errico and Lawson compared two assemblages of bone pipes, from Upper Paleolithic and European Medieval sites, with a “controversial find” of a bone flute at a Slovenian Middle Paleolithic site (2006:42). Dating from 21,000-27,000 years BP, the Upper Paleolithic assemblage demonstrated regular spacing of finger holes (typically n=4) and hatch marks for “tuning” consistent with medieval pipes. In contrast, the Divje babe flute only exhibited two “finger holes” and was damaged at both ends, leading the authors to deliberate whether this condition was the result of taphonomic processes. After examining 77 perforated bones from the same site, it was determined that the “finger holes” were consistent with punctures created by carnivore damage (d’Errico and Lawson 2006:46-50). As a result d’Errico and Lawson put forth a series of “music-archaeological criteria” building on the foundations laid by Lund’s probability groupings (1981) and evidence from the material record which apply to both artifacts and to “acoustic monuments.” These criteria are meant to investigate intentional use of artifacts and features as sound producing devices as follows: (A1) feasibility – does it produce sound; (A2) do ethnographic parallels exist; (A3) is there ancient documentary
support; (A4) is there contemporary archaeological support; (A5) is the design efficient; (B1) do non-contemporary archaeological parallels exist; (B2) do the context and association support “acoustical behaviors”; (B3) does the manufacture or exploitation suggest use for acoustic purposes; (B4) are there multiple indications of consistency of form; (B5) are there patterns or relationships to earlier/later examples of a similar kind; (B6) are the design choices/materials appropriate; (B7) do practical contra-indications exist (i.e., is it inconsistent or impractical); (B8) are essential acoustic features absent; (B9) evaluation of B7 – how much needs to be explained away for the interpretation to make sense; (B10) evaluation of B8 - do features need to be “invented” for the interpretation to make sense (d'Errico and Lawson 2006:46-50). In answering these questions, researchers could evaluate the potential of sound producing devices, while also exposing “wishful thinking” biases.

**Reflexivity and Engagement in Archaeoacoustics and Archaeomusicology**

While the works of Lund (1981), Cross and Watson (2006) and d'Errico and Lawson (2006) established replicable and scientific methodologies for the investigation of the acoustical properties of individual sites, features, or artifacts, inter-site or landscape studies remained noticeably absent from consideration until the twenty-first century and

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3 The “A” series is specifically cited as a derivative of Lund’s (1981) work.

4 For “acoustic monuments” this is further subdivided into (B2a) external context and associations, referring to the “surrounding landscape and relationship with other sites”; and (B2b) internal context and associations, or the on-site archaeological record (d'Errico and Lawson 2006:54).
appear to be tied to further technological advances or incorporation of multidisciplinary approaches. Work with individual sites or artifacts continued to develop, however, and incorporate the critical and reflexive approaches that these researchers advocated.

In contrast to the large body of work at megalithic sites, Mills presented a multifaceted archaeoacoustic investigation of the sounds of daily life at Çatalhöyük, Turkey (2004, 2014). Houses at Çatalhöyük showed little differentiation, indicating a house-level social structure. Given this information, Mills asked: could tasks performed inside or outside a building be heard through the walls? Did the architectural materials impact sound transmission? What were the dominant sounds? (Mills 2014:151-4). To answer these questions archaeologists working at the site participated in “soundwalks” and discussions about past and present sounds on site to encourage reflexivity. Then, tasks were performed within an experimental house and digitally recorded using binaural omnidirectional microphones worn by those performing the tasks. The sound producing activities were performed within all spaces of the house, including storage spaces and the roof, and consisted of sweeping, making and applying plaster, polishing the walls, grinding, moving vessels and pottery within the house, singing, and speaking. A sample of these recordings were later played back on a loop to provide an auditory experience to visitors of the site (Mills 2004, 2014:157-75). This study promoted both subject centered survey and experimental archaeology to create a reconstruction of the sounds of everyday life providing the public with an engaging somatic experience.

Incorporating appropriate ambient sounds adds a dimension of experience to more recent historical interpretations as well. At the Falkland Estate in Fife, Scotland, several
acoustic reconstruction projects were undertaken to promote a synesthetic experience for the visiting public. Originally used as a royal hunting park in the 1450’s the site was later modified in the Victorian era with the addition of monuments and other features to the manicured landscape (Chapman and Wilson 2010: 232-3). For the first project, sounds of deer, hunting songs, archery, stables and riding, and falconry were blended with ambient environmental sounds recorded on the estate to create four six-minute tracks. These were played from four pairs of stereo speakers arranged within a hallway of the estate, where a 30m long seventeenth-century tapestry depicts the estate’s use as the king’s hunting grounds. Due to the length of the tapestry and the enclosure of the hallway, the sounds would be blended for each “audience” member as they progressed through the gallery, providing an individual sonic and visual experience (Chapman and Wilson 2010: 233-5).

For audio walks within the estate’s grounds Chapman and Wilson recorded a variety of sounds including “off season” ambient sounds; music and “micro-dramas” based on historical use of the estate; interviews with experts on the estate’s grounds, geology, and hydrology; and provided access to visitors at various locations on the estate. This allowed the visitors to experience the present ambient environment while walking between site features and recordings to promote interaction with “the actual sonic environment” (Chapman and Wilson 2010: 233-5).

This focus on engagement with the public can also be found in recent archaeomusicology. In 2017 Katz’s Maya Music Project set out to document and reconstruct Maya instruments through 3D scanning and printing. By visiting a variety of
collections, Katz was able to create a database of 430 Maya instruments of which 160 were 3D scanned. Artifacts were digitally captured using photogrammetry, edited manually based on measurements taken by hand from whole and fractured instruments, and 3D printed (Katz 2017:30). Acoustical comparisons between the originals and replicas were made using spectrograms to determine frequency or pitch, and if necessary corrections and reprinting occurred. The implications of this work are twofold: for archaeologists, this process allows recreation of playable instruments for their research, as well as a method for recreating or restoring fractured or destroyed instruments. For the public, the availability of replica artifacts allows for a tangible engagement with the past (Katz 2017:31-3).

In an exploration of perception and perspective similar to Watson’s (2006) investigations of intentionality, Scullin and Boyd (2014) questioned the categorization of sounds and noise in Moche society. The Moche, who occupied Peru’s north coast from approximately 100-900CE, created a variety of sound producing devices and instruments including: bone flutes, metal bells and rattles, shell trumpets; and many ceramic versions of these instruments including: rattles, ocarinas, whistles, whistling bottles, trumpets, and imitation shell trumpets (Scullin and Boyd 2014:368). At the Huacas de Moche urban center, 419 ceramic whistles were recovered, primarily from patio or food-preparation areas, representing half of all sound producing devices found at the site (Scullin and Boyd

5 Although it is beyond the scope of this dissertation, the prospect of having access to reconstructed instruments could provide researchers with additional modeling inputs to use with the tools discussed in Chapters 5 and 6.
One hundred eleven of these whistles were played and recorded, and decibel levels and frequencies were measured. At 1 meter from the sound source, the average decibel level for each whistle was 89 dB, with the majority of pitches and frequencies (approximately 80%) in the octave 7 range (the highest octave on a piano). To the ear, the sounds produced by these whistles were generally louder than a human voice and produced a variety of pitches and microtones, which the authors describe as “sounding ‘out of tune’…according to Western musical sensibility (Scullin and Boyd 2014:373-6).” The widespread prevalence and use of whistles provided evidence that the Moche soundscape could be very loud, and demands we consider concepts of sound and noise within varying cultural contexts.

A reflexive approach is also apparent in Kolar’s statement that the acoustics of the past should be “understood as interactive physical dynamics that influence human experience and behavior (2013:13 emphasis in original)” and use of a psychoacoustic approach to studying site acoustics. To explore human experience of sound, Kolar examined the perceptual and cognitive responses of survey participants to the sounds of Andean Formative Period aerophones when played within two galleries of Chavín de Huántar, Perú (Kolar 2013: iv, 21, Kolar 2017:42). Specifically, Kolar studied auditory localization, or the human perceptual orientation mechanism⁶, which explores the perceived sound source location within the acoustical and architectural environment of Chavín de Huántar.

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⁶ Described in Cross and Watson as “objective envelopment” (2006:110-113) and further discussed in Chapter 4.
the galleries. The architecture of the galleries results in standing waves, which are felt as pulsating air pressure patterns (Kolar 2017:40). As in the past, participants experience both commonalities and subjective individual experiences when listening in sound environments, and more robust conclusions are provided by working with a large group of participants (in Kolar’s case 45 people consisting of both English and Spanish speakers) rather than focusing on single first person researcher observations (2013:13, 21; 2017:49).

Recordings of replica “pututus” (shell horns) were played back over single-driver loudspeakers from plausible past performance locations, and 35 combinations of source-listener tests were performed in a variety of sound transmission paths. Architectural features influencing the spread of sound within the galleries included corners, ducts, rooms, cells, levels, and number of paths (Kolar 2013:30-3). Participants recorded whether sounds were perceived to come from above, below, in front, behind, left, or right of them and the estimated distance to the sound source. Once compiled, the data revealed that the architecture, functioning as a waveguide, caused listeners to perceive sounds as emanating from the closest aperture while perception of distance from the sound source was influenced by acoustic resonance. These factors, combined with others, lead Kolar to conclude that the architecture of the Chavín galleries could be “leveraged” to manipulate the experiences of those within (2013:37, 54-62).

To determine whether acoustics were correlated with paintings in open-air Levantine rock shelters, Díaz-Andreu and García Benito produced and analyzed sounds on site at various rock art and control locations within La Vallorta Gorge in Spain. Sounds
were produced using a combination clapping, whistles, male and female voices and were recorded using a 2 channel digital recorder. Data was also collected on field forms (see Díaz-Andreu and García Benito 2012:3595), including the type date and location of tests, plus notes about ambient sounds, direction of echoes, presence-description/absence of rock art and other data. Free software was used to produce spectrograms and results were interpreted based on the resonance and echoes at each site (Díaz-Andreu and García Benito 2012:3592-3). Results indicated that major painting sites possessed the highest resonance values, although all painting sites had positive results for echoes. Outside the painted areas and in the control sites, resonance and echoes were not detected, leading to a determination that Paleolithic rock shelters with good acoustics were selected for painting (Díaz-Andreu and García Benito 2012:3596-7).

The use of a combination of field forms and acoustic measurements in the studies of Kolar (2013, 2017) and Díaz-Andreu and García Benito (2012) shows the importance of incorporating the objective (sound physics) and subjective/perceptual (psychoacoustics) in archaeological study. As discussed further in Chapter 4, human auditory perception, though dependent on the physical properties of sound, is distinct from it. It is this combination which creates a variety of experiences and interpretations grounded in biology and cultural identity.

**Use of Acoustical Science Standards in Archaeoacoustic Methodologies**

Following the suggested “standards” of Cross and Watson (2006), recent archaeoacoustic methodologies have explicitly drawn on standard acoustical procedures
established by various national and international standardization organizations. One of the most popular methods of studying the acoustics of enclosed spaces today is the Impulse Response method, detailed in ISO 3382-2 (2008). Briefly, impulse response is defined as the “temporal evolution of the sound pressure observed at a point in a room as a result of the emission of a Dirac impulse at another point in the room (ISO 2008:2).” Typically, impulse response studies involve sound production through an omnidirectional source measured at a receptor location with an omnidirectional microphone and system for displaying decay curves (ISO 2008:3). Although many early studies featured components of, or similar to, those used in impulse response studies (Devereux and Jahn 1996; Jahn et al. 1996; Reznikoff and Dauvois 1988, Waller 1993a, 1993b; Watson and Keating 1999; Watson 2006) the majority of these applications predated archaeologists’ adoption of the standard acoustical science methodology (Waller (2002) is a notable, if not explicit, early adopter). The impulse response method has been used in virtually all recent investigations of caves, tombs, and walled architectural or natural features.

In 2002 Waller explored the correlation of echoes and rock art within the Hieroglyphic Canyon, and recorded the ringing rock at Painted Rocks State Park, both located in Arizona. Impulse sounds were created using a specialized spring-loaded device which allowed for standardized sound intensity, echo delay, and impulse generation. Ambient sounds were recorded using an omnidirectional microphone and portable cassette recorder, and the recordings were digitally analyzed using specialized software (Waller 2002:14). Within the Hieroglyphic Canyon, the most densely decorated areas corresponded to areas of maximum sound reflection intensity, while reflections
were still recorded at other areas will fewer decorations. Flat, and otherwise “suitable” decoration surfaces which had the lowest decibels of reflection were notably undecorated. At the Painted Rock site, the ringing rock was shown to have both an increased resonance time, and higher main resonance frequency than the control location (Waller 2002:14).

In 2014 Iannace et al. conducted an impulse response study within the San Gennaro and San Callisto catacombs, located in in Naples and Rome, Italy, respectively, seeking to determine whether the catacombs could have been used by early Christians (c. 500 CE) for meetings or religious functions. Sounds produced by popping balloons were measured by an omnidirectional microphone connected to a laptop, and the software dBBATI was used to analyze the ISO 3382-2 (2008) parameters Reverberation Time ($T_{30}$), Early Decay Time (EDT), Clarity ($C_{80}$), Definition ($D_{50}$) and Speech Transmission Index (STI) (Iannace et al. 2014:583-4). In the lower level of the San Gennaro catacombs, a high degree of speech intelligibility was indicated by the results, whereas at the second level much of the speech was absorbed by the porous walls and floors. The San Callisto catacombs also exhibited a high degree of speech intelligibility, and orators could have been correctly understood by the congregation, leading the authors to conclude that these spaces could have been used for services consisting of prayer and recitation of liturgy (Iannace et al. 2014:586-9). A similar method of analysis was used by this group of researchers to investigate the acoustics of the Large Theater of Pompeii (Iannace et al. 2013), three Italian cave systems which are still used for performance events today (Iannace and Trematerra 2014), and the Cumaean Sibyl cave
in Naples Italy (Iannace and Berardi 2017) establishing a replicable scientific basis of study.

Impulse Response and other acoustic methodologies were also applied by Till in a multi-season exploration of five Paleolithic rock art caves in Spain as part of the “Songs of the Caves” project. These methods were applied to seek connections between acoustics and imagery, and to explore Neolithic and early Bronze Age experiences. Among the acoustic metrics collected, recorded, and analyzed for statistical correlation were $T_{30}$, EDT, STI, $C_{80}$, $D_{50}$, Lateral Energy (LEF), and Envelopment ($L_{G_{80}}$); however, the study also included literature review, experimental archaeology and public engagement to provide archaeological context (Till 2014:296-8). Sounds produced or studied included those of instruments (bone flutes, drums, and song), and sounds of the caves (water dripping, “playing” stalagmites as lithophones). Similar to Watson’s discussion of intentionality (2006), and Scullin and Boyd’s examination of Sound vs. Noise, Till posits that there need not be a distinction between categories such as music, intent/function, or “background” sounds – rather that these should be taken together as “total acoustic ecology” to understand the interplay of visual and auditory components of experience within the context of a site (Till 2014:300).

While many researchers have applied impulse response studies to archaeoacoustics, special note must be made of a pair of today’s most prolific researchers: Díaz-Andreu and Mattioli. Whether working together or with others, they have applied their techniques to a series of rock art studies at sites in the western Mediterranean (Díaz-Andreu et al. 2019), central Mediterranean (Mattioli et al. 2017), and
Spain (Díaz-Andreu et al. 2014, 2017; Díaz-Andreu and García Benito 2015; Mattioli and Díaz-Andreu 2017). Díaz-Andreu and Mattioli (2016) cite three measurable acoustic parameters that can be used to investigate the soundscapes of rock art: echoes, resonance, and reverberation. Although these methodologies are not novel, as attested by several works cited above (Devereux and Jahn 1996; Jahn et al. 1996; Reznikoff and Dauvois 1988, Waller 1993a, 1993b; Watson and Keating 1999; Watson 2006) the authors situate these effects within the physical processes that impact sound, including impulse response parameters such as Reverberation Time and Early Decay Time (Díaz-Andreu and Mattioli 2016:1049-50).

Díaz-Andreu and Mattioli’s investigation of rock art sites typically consists of both decorated and control (undecorated) sites (Díaz-Andreu et al. 2014, 2017; Díaz-Andreu and García Benito 2012; Mattioli and Díaz-Andreu 2017). Impulse sounds are produced multiple times at each site to allow variable placement of the location of the sound source and receiver during each test (e.g., investigation of sites north of the Celemín River in Spain in Díaz-Andreu et al. 2014:9 Figure 8). For open air sites, additional methodologies from acoustical physics are also applied, including the Ambisonics technique, which investigates echolocation properties through the parameters of different time of arrival (TOA) and Interaural Level Difference (ILD) which describe how and when sounds reach each ear (Mattioli et al. 2017:14). Acoustic recordings are made in the field for all studies, and software is used for post-processing and analysis. As the methodologies these researchers employ have evolved, their hypotheses do so commensurately, shifting from investigations of the correlation of rock art and acoustical phenomena locations (Díaz-
Andreu and García Benito (2012) to studies examining site resonance and echoes based on the style of artwork present (Díaz-Andreu et al. 2014).

In 2018 Liwosz undertook an acoustical analysis of petroglyphs located within two Mojave Desert gorges at Death Valley and Fossil Falls/Little Lake in southern California. Petroglyphs within the Mojave Desert were primarily created by “pecking”, a percussive stippling method which results in rhythmic sound. Following Díaz-Andreu and Mattioli (2016) and Waller (2004), Liwosz performed impulse response tests by percussing quartz hammerstones against a portable limestone tablet, and in subsequent field seasons added shouting and clapping to the sound sources. Liwosz also supplemented this analysis with sine sweeps and researcher observations to locate the limits of audibility, then the canyons were then divided into zones of interaudibility (2018:209-212). Three such zones (“soundsheds”) were identified for the Death Valley site, corresponding with changes in bedrock geology, and discontinuities between the audibility and visibility of the speaker were noted (Liwosz 2018: 236-7). At the Fossil Falls site, six study locations exhibited reverberation, corresponding with iconography of the fertility/renewal complex (Liwosz 2018:402). In sum, Liwosz determined that acoustic phenomena were “correlated with dense concentrations of petroglyphs” and that oral evidence suggests these phenomena were attributed to “other-than-human inhabitants of these spaces (2018: 490).” In addition, he concluded that the petroglyphs in these areas served as mnemonic devices for prompting narrative, song, and performance (Liwosz 2018: 491).
In addition to the incorporation of acoustical science standards, multidisciplinary archaeoacoustics has also begun to feature computational approaches and modeling strategies. To determine how loud (at what Sound Pressure Level (SPL)) noted evangelist George Whitefield addressed a 1739 Philadelphia crowd and how many people within the crowd could hear him clearly, Boren used AutoCAD to create a scaled 3D model of Philadelphia’s Market Street with building locations and dimensions derived from contemporary drawings and maps. These historical sources were also used to inform the acoustic absorption and reflectivity data for various construction materials (e.g., brick, wood, glass) and the gravel road (Boren 2016:3-6). CAD modeling, historical temperature data, and vocal sound pressure levels (see Boren et al. 2013) were input to the CATT-Acoustic v9.0 geometric acoustic modeling program and absorption coefficients were used to simulate a crowd (Boren 2016:12-4). Utilizing a minimal STI value of 0.3 and taking directivity into account, Boren calculated the Minimal Intelligible Area (MIA) for Whitefield’s address. By further combining known crowd and area measurements from three London sermon locations, Boren determined that Whitefield could have been heard by a crowd of approximately 20,000-30,000 people in Philadelphia, potentially reaching up to 50,000 people in the public spaces of London (Boren 2016:14-20).

This work has larger implications for the efficacy of public address in historic and pre-historic times. Although the acoustics of the built environment must be taken into account, this study shows that it would be possible for accomplished orators to be understood by large numbers of listeners without the use of amplification. In addition,
Boren et al.’s (2013) work provides replicable modeling input data for the Sound Pressure Levels of trained orators.

In a similar study, the Virtual Paul’s Cross project, Azevedo, Markham, and Wall (Azevedo et al. 2013, Markham et al. 2013, Wall 2018) explored the archaeoacoustics of John Donne’s Gunpowder Day sermon, which was intended to be given from the Paul’s Cross outdoor preaching station at St. Paul’s Cathedral in London on November 5, 1622 in a space measuring 22,500 ft² (Azevedo et al. 2013:1-2). Citing historical records, Wall contextualizes the sermon as a performance, and the delivery of the sermon was replicated by an actor based on records of Donne’s preaching style (2014). Sounds of a crowd were reproduced by a combination of recordings and scaling algorithms, and sounds of a church bell were reproduced from modern correlates and modeling. These sounds were then combined with a 3D SketchUp model of Paul’s Cross and St. Paul’s Cathedral and evaluated using CATT Acoustic (Azevedo et al. 2013:3-4). While it was determined that Donne could have addressed a crowd of 5,000 people, this was not the end of the project. Artificial Intelligence was used to simulate crowd responses to the sermon, additional ambient sounds were added, then a media gallery was created to allow virtual experience of the sermon7 (Azevedo et al. 2013:5, Wall 2018).

In 2018, Goodwin recreated ancient Maya soundsheds through a combination of fieldwork and Virtual Reality. A portable stereo recorder was used to capture ambient

7 https://vpcp.chass.ncsu.edu/
sounds at Copán, Honduras, particularly those including birds, then the recordings were reviewed and edited using Audacity (software) to exclude modern sounds and create ambient tracks. The DearVR plugin was used to incorporate the audio tracks into the VR environment containing a 3D reconstruction of the city, simulating the audibility of sounds based on the listener's VR “location.” This program was chosen because it replicates auditory effects including occlusion, obstruction, and distance correction (Goodwin 2018:18-9). This study also included a preliminary investigation of reverberation time and speech intelligibility calculated using a combination of data on the likely number of performance attendees, sound physics formulae, 3D modeling, and sound absorption coefficients defined using modern architectural materials as correlates (Goodwin 2018:30-2, 38-9). While work is ongoing, initial results revealed that approximately 5-10% of Copán’s population could have heard and understood a speaker within the East Court, an area reserved for elites (Goodwin 2018:40).

GIS and Landscape Scale Archaeoacoustics

Beginning around 2004, archaeologists began to explore the possibility of exploring soundsheds and audibility at the landscape scale, often through Geographic Information Systems (GIS) technology. Up to this time and beyond, many researchers considered the possibility, though often cited a lack of tools and/or methodology to further pursue GIS approaches to archaeoacoustics (Constantinidis 2004; Díaz-Andreu and García Benito 2012; Díaz-Andreu and Mattioli 2016; Frieman and Gillings 2007; Tilley 2008).
In a methodological marshalling, Constantinidis (2004) outlined the need for work in this arena, as well as potential courses of action. Although tied to settlement theories\(^8\), Constantinidis described the value of integrating seasonal audibility analysis with existing seasonal visibility and least-cost-path information (i.e., courier routes) in studies of inter-site communication. Although specific methods were not provided, the use of Digital Elevation Models (DEMs) and “sound algorithms” which considered terrain were suggested as a basis for investigation (Constantinidis 2004:258-61). These suggestions hinted at one method of applying GIS to the study of sound: through the use of calculations and models.

Contemporaneously, Mlekuz noted that available GIS software reflected a Western bias towards vision as the dominant mode of perception, suggesting the development of new models which included space and topology (i.e., how to represent “spaces of perception”), time, scale, and representation of agents (Mlekuz 2004: Section 3.0). Mlekuz developed a GIS model to explore the role of sound in the Christianization of late medieval (fourteenth to fifteenth century CE) Slovenia (2004: Section 4.1). While recognizing that multiple factors influence sound propagation (air absorption, wind and temperature, surface and barrier effects, etc.) Mlekuz noted the primary importance of

\(^{8}\) While the primary theoretical milieu of this dissertation lies in Landscape Archaeology, Phenomenology, and Performance Theory, settlement theories provided much of the impetus for detailed site mapping. As mapping presents a crucial component of a GIS approach, the importance of settlement theories to the development of spatial archaeology will be considered in Chapter 3.
“soundmarks” or “stable or long-term properties of a landscape,” such as topography, in GIS modeling (2004: Section 4.2).

Mlekuz’ model operated by calculating spherical spreading losses and barrier effects from which a binary acoustic horizon was created indicating areas of audibility or inaudibility. To approximate the impacts of other environmental factors on sound propagation as described above, additional calculations were then performed on the binary raster to create a “fuzzy acoustic horizon” per Gillings (1998) and Openshaw and Openshaw (1997) which results in a gradation of increased audibility nearest the sound source, and decreasing audibility with distance and intervening topography (Mlekuz 2004: Section 4.3). Although this model provided a way to visualize and identify soundscapes, Mlekuz emphasized the importance of contextualization (identity, gender, social networks, etc.) in interpretation of modeling results (2004: Sections 4.4-5.0).

In a more recent application of GIS for acoustic modeling, Díaz-Andreu and colleagues used GIS to investigate the soundscapes and viewsheds of the Alicante Mountain rock art landscape (Díaz-Andreu et al. 2017:194). Visibility studies were completed using a combination of ArcGIS 9.3’s viewshed tool (binary output) and the Higuchi method (1983, see also Wheatley and Gillings 2000) and soundsheds were calculated using SPreAD-GIS 2.0. Modeling inputs included a Sound Pressure Level of 90 dB measured at 1m with a frequency of 1500 Hz (representative of both prehistoric instruments and the human voice); use of an existing 2006 Land Cover dataset; and meteorological data representative of an average day in July with no wind. Resulting soundsheds were also clipped to the Higuchi medium area viewshed to represent
locations where sites were simultaneously audible and visible (Díaz-Andreu et al. 2017:197-199).

The findings of this study suggested that artists at sites featuring Schematic designs were much more interested in greater areas of visibility and audibility than those working in the Levantine or Macroschematic styles. In addition, Levantine artists appeared to have no directional preference to their viewsheds, while Schematic artists had such a strong preference for south facing sites, that if Schematic art was collocated with Levantine or Macroschematic designs, southern directionality was favored. Thus over time preference shifted from localized acoustical effects within a site, to greater landscape scale visibility and audibility (Díaz-Andreu et al. 2017:205-6).

Another popular method of soundshed mapping involves the collection of acoustic data in the field and transferring that data into GIS. In 2015 Scullin mapped the sound at Huacas de Moche, Peru, following this method. Continuing her work with Moche instruments and sound producing devices, as described above, she placed an omnidirectional speaker emitting pink noise at three sound source locations at Huacas de Moche and calibrated the speaker to produce sounds in the range of 95-100 dBa (100-105 dBC), the highest known sound pressure levels for Moche instruments (Scullin 2015:318-321; see also Scullin and Boyd 2014). Surveyors with GPS and sound level meters proceeded outward from the speaker along transects, taking decibel level measurements, GPS locations at 10-20 meter intervals. At each location survey forms were completed with the following information: “Site Name, Recorder’s Name, Date, Speaker Location, Weather, Time, Silent dBa, Silent dBC, Maximum dBa, Maximum dBC,
Type of Sound (white, pink, red, other), GPS location, Interior or Exterior of Architecture, Ability to Hear Speaker, Ability to See Speaker, Observations About Visual Field, Observations About Sound, and Additional Observations (Scullin 2015:321-2)." The same methods were repeated in absence of the sound source to create a map of the ambient soundshed in GIS.

Analyzing the sound maps, Scullin investigated performances at each of the three sound source locations: one atop the platform at Huaca del Sol, and two locations at Plaza 1 of Huaca de la Luna. High frequency sounds produced at Huaca del Sol were not audible at Huaca de la Luna (approximately 550-600m away), while lower frequency sounds were quiet, but audible. A similar pattern was seen in the reverse, though sounds reaching Huaca del Sol were even more faint, indicating a correspondence between the maximum spread of sound and the locations of the Huacas. All those occupying the Urban Zone between the Huacas would have been within the passive audibility zone of performances at either location (Scullin 2015:326-339).

In their 2017 study of rock art shelter locations in Extremadura, Spain, Mattioli and Díaz-Andreu explored “canyon effects” on outdoor sound propagation, whereby the concave vertical surfaces of the shelters could reflect or concentrate sounds creating areas of “augmented audibility” (2017:83-4). Fieldwork for the study consisted of using a loudspeaker to emit a sine-sweep signal while data was recorded in a series of rock shelters with and without petroglyphs. Each receiver position was recorded approximately 30 times. Then the data was analyzed by Adobe Audition v 1.5 to calculate the A-weighted Equivalent Sound Pressure Level. The resulting averages were compared to predicted
“Transmission Loss” data (calculated as spherical spreading losses only) to determine differences in audibility. At the undecorated sites, recorded attenuation values were within 1% of the predicted distance attenuation values, while at painted sites a 13% decrease in recorded vs predicted attenuation was observed, leading to the conclusion that rock art locations are correlated with areas of augmented audibility (Mattioli and Díaz-Andreu 2017:86-90).

Kolar et al. (2018) also created sound maps to investigate the acoustical properties of communication between Inca governors and the populous at administrative sites. Speakers would address the crowds while standing on raised structures (*kallankas*) which allowed them to be heard, but also emphasized the division between the rulers (elevated, closer to supernatural objects) and the people standing the within the plaza below (Kolar et al. 2018:2-3). At Huánuco Pampa, Peru, a pre-contact site dating to c.1400 CE, a large *kallanka* (32.5 x 48m) rises 4.5m above the plaza below. Sound transmission from the platform was studied by determining sampling points from archaeological and documentary records; documenting and recording test signals; applying acoustical metrics of outdoor sound propagation; and recording psychoacoustic perceptions (Kolar et al. 2018:5-6).

Sound sources included standard audio test signals, and human produced sounds, including the sound of a male voice, a “pututu” shell trumpet, a metal safety whistle, wooden percussion clappers, and a loudspeaker for playing an exponential sinusoidal sweep “ESS” (Kolar et al. 2018:6-9). Each sound source was played from two source locations, and a combination of sound level meter readings, researcher observations, and
audio recordings were created or documented at eight receiver locations. Results were compared with “predicted” (i.e., calculated) free field spherical spreading losses, and it was determined that for higher frequency sounds, atmospheric attenuation resulted in additional sound level decreases, while wind accounted for additional interference (Kolar et al. 2018:12-15). In addition, at the furthest receiver locations measurements taken in the field indicated the sound of a male voice retained higher than expected sound levels, while the clapper sound levels were much lower than predicted, suggesting the importance of source directivity. Finally, analysis revealed that the walls of the *kallanka* acted as barriers, creating sound shadows. As such, someone standing within the plaza nearest the platform may have had difficulty seeing or hearing the speaker directly above (Kolar et al. 2018:17-19).

Kolar et al.’s (2018) study is of note for several reasons, but of primary importance to the subject of this dissertation is the study’s combination of fieldwork completed using rigorous methods, and use of predicted sound levels. Although the predicted sound levels in this study consisted of spherical spreading losses only, fieldwork indicated the importance of atmospheric and barrier attenuation to the transmission of sound. As further described in Chapter 5, these factors have been included in the Soundshed Analysis Tool to improve the accuracy of estimated soundsheds produced through computer modeling. In addition, both Scullin’s (2015) and Kolar et al.’s work provide replicable modeling input data for study (see Kolar et al. 2018:15, Table 1), along with the work of Boren et al. (2013) as noted previously.
Discussion

Each of the above studies framed the advancement of archaeoacoustics methodologies, from the seminal investigations and classifications of Lund’s “sound producing devices” (1981), to the roadmap of archaeoacoustics methodologies established by Cross and Watson (2006) and d’Errico and Lawson (2006). Features of these studies which have directly impacted the work described herein include:


2. the use of GIS to model soundsheds at various cross cultural locations furthering work proposed by Constantinidis (2004), Díaz-Andreu and García Benito (2012), Mlekuz (2004), and others; and a tradition of mapping sound locations that extends back to the earliest archaeoacoustic studies (Devereux and Jahn 1996; Jahn et al. 1996; Reznikoff and Dauvois 1988; Watson and Keating 1999) (see Chapters 7-9); and

3. a careful consideration of the results of modeling in each of the case studies to situate the results within the appropriate perceptual perspectives in the manner

Although the case studies presented here do not currently feature fieldwork components, sound mapping exercises (particularly those similar to Scullin (2015) and Kolar et al. (2018)) are the logical next step in improving the model (see Chapter 10).
Chapter 3. Theoretical Perspective: Landscape Archaeology and Phenomenology

“Every archaeological school has long realized in its own intuitive and tacit manner the information latent in archaeological spatial relationships – this much is clear from the otherwise unwarranted precision of many of the maps and ground plans going back into the eighteenth century and the early intuitive manipulations of distributions or the meticulous three-dimensional location of artifacts in some early excavations.”

(Clarke 1977:6)

I have always found Clarke’s statement to be of profound significance to any form of spatial analysis and associated interpretation. In a post-processual world, theory and spatial analysis methodologies have at time seemed like feuding siblings, full of misunderstanding and distrust (Brouwer Burg 2017; Verhagen and Whitley 2012) or rejecting each other outright (e.g., Tilley 2004: 218), yet the fact remains that, as Clarke noted, archaeologists of varying specialties and perspectives intrinsically value spatial data (e.g., Bauer et al. 2004; Chisholm 1968; Clarke 1977; Gillings 2012; Griffin 1956; Jones et al. 2012; Hodder 1972; Kvamme 1990; Ritchie and Funk 1973; Sears 1956; Steponaitis 1978; Tilley 1994; Trigger 2006; Vandrei 1987; Vita-Finzi and Higgs 1970; Williams 1956; Willey 1953).

Use of GIS in particular has been at the heart of these debates. While GIS is a tool, forming only part of most methods and methodologies, it has often been
misrepresented as a theory or assigned theories inappropriately. As described by Verhagen and Whitley, “…many researchers working with GIS and statistics have given up the fight altogether and keep on working in a processual framework—without drawing overt attention to this in their own writings (2012:50).” Dobres and Robb describe the traditional archaeological process as beginning with theory, which informs methods/methodology and data collection, leading to interpretation, explanation, and modeling (2005:165). While they support a non-linear, “interdigitating” approach (Dobres and Robb 2005:164), looking at this traditional study format it is easy to see why models that are not grounded in theory are treated with “suspicion” (Verhagen and Whitley 2012:55).

Brouwer Burg tells us that the point and click simplicity of GIS can be to blame, as the user must have a combination of familiarity with the functionality of GIS tools, an understanding of process biases, and “a solid grasp of the underlying theoretical concepts regarding geospatial analysis and socionatural processes” to utilize GIS effectively as a research tool (2017:115). It is, therefore, important, continuing the family analogy, to remember and acknowledge the theoretical roots of GIS methodologies, while revealing how GIS methodologies have matured beyond reliance on ecological theories alone. When modeling the spatiotemporal components of auditory perception there is much to be gleaned from several theoretical milieus, including phenomenology, ecological psychology, performance theory, and other approaches as I will return to at the conclusion of this chapter.
The “First Age” of Theory in Spatial Modeling: Processual/Ecological Roots

As Clarke’s quote suggests, the quantifiable relationships of extant and modeled spatial variables has been occupied by an ever evolving body of theory attempting to explain those relationships while identifying and controlling for bias inherent in previous theoretical and methodological approaches. This reactionary evolution of ideology that contributed to the “First Age of Modeling” (Kvamme 2005:2) originally developed from three major underlying influences: economic theory/site catchment analysis; geographic/central place theory; and systems theory/hard science.

When data was collected by archaeologists in the field often tied it to the first or second modeling ages. At the apex of the “First Age of Modeling,” processualist theory combined with statistical methodology to advance the exploration of predictive modeling and landscape scale site location studies. Much of this work focused on the identification of biases, assessing the performance of models, and utilizing/quantifying environmental variables for study. These early studies were limited in scope due to technological constraints (Kvamme 2005:4).

Works such as Stafford and Hajic's study of the middle archaic hunter gatherer population of western central Illinois utilized the artifact assemblage to map settlement strategies and investigate movement over geographic zones (1992:138-43). Ecological interaction concerning the use of the landscape was considered at three scales: the migratory range of the people (middle scale of movement), the foraging range (smallest scale of movement), and the largest scale extended trade networks. Using log likelihood
tables for analysis to explore the relationship between topography, deposition, and settlement strategies; statistically derived patterns such as low or high bulk resource procurement and rates of site reoccupation were used to draw conclusions about human behavior (Stafford and Hajic 1992:152-8).

Authors Dewar and McBride called their attempt to control for modeling biases “remnant settlement pattern analysis.” They believed that distortion often occurred in landscape scale settlement studies when archaeologists assumed the continuity of the physical landscape and of archaeological sites over time, and that the processes contributing to these distortions should be delineated (Dewar and McBride 1992:226-8). Assuming that perfect preservation and identification of sites was possible, there are several potential site occupation/reoccupation sequences which would form the archaeological record. The same area could have been inhabited in a series of ways including a dispersed sequence of occupations, a localized sequence of reoccupation with some congruence, or a concentrated sequence of congruent reoccupation; which leave a large, clustered, or single point footprint respectively. In each of these cases, an equal number of sites with access to the same resources would all appear differently when plotted on a map (Dewar & McBride 1992:234-5).

The “First Age of Modeling” also saw an increase in the importance of Geographic Information Systems (GIS) in settlement studies. Rossignol, for example, questioned the idea of “sites” as a unit of analysis, and purposefully combined taphonomy, ethnoarchaeology, geomorphology, and context to suggest constant reevaluation of methods, theories and concepts relating to settlement analysis (Rossignol 1992:4). Rossignol’s actualistic approach to studying the dynamic systems which create and
influence the archaeological record asked researchers to consider the uniformitarian constants of cultural and ecological interplays operating through time; the reasoning for spatiotemporally situated human behavior; and how patterned changes in diverse behavior could be studied (Rossignol 1992:14).

This approach could be seen in Schlanger’s study of ancestral Puebloan sites in the uplands of the Dolores River in southern Colorado. Schlanger combined sites with isolated finds to elicit information about landscape areas that were recurrently used/occupied and abandoned by a group during their long term use of the landscape; termed “persistent places” (Schlanger 1992:92). Investigations included mapping a sample of 175 habitation loci sites with evidence of buried structures; 202 limited activity areas without architectural remains; and 62 isolated finds within a 24.5 square kilometer study area. Evidence of repeated use was found at 31 “persistent places”, of which only half were habitation loci (Schlanger 1992:100-1). Visual inspection of the resulting distributions indicated that reoccupation was most likely influenced by: access to the uplands via breaks in the river canyon walls, and proximity to the southern wetlands which were variously inundated during the long term occupation of the area (Schlanger 1992:93,105).

In addition to the examples cited here, a number of studies which typify the “First Age of Modeling,” included: those focused on the scientific analysis of archaeological data, with basic components such as the objective definition of an assemblage or dataset, the quantification of data, and the testing of hypotheses (Binford and Binford 1966; Binford 1972); investigations focused on regional site distributions as correlates of human choice shaped by political, socio-economic, environmental, and other features

While ecological factors and procurement strategies dominated the hypotheses used to investigate these sites, the methodological modeling advancements that occurred as a result of these lines of inquiry persisted, informing future works. These included a focus on temporal and taphonomic aspects of intersite relationships, as well as an incorporation of networking and interactions between sites. Where processual theories sought to explain regularities and patterning in locational analysis, post-processual approaches focused on differences and variation in the cognitive and social facets of location (Kvämm 2005; Seibert 2006). Although it preceded post-processualism, this theoretical perspective manifested itself at the site level scale in Cultural Geography, or Rapoport’s “Environment-Behavior Studies” (1977; 2006). By Rapoport’s definition, the built environment of a settlement is organized based on culturally governed cognitive choice processes, which create cultural landscapes that communicate ideals, values, and symbolism that possess meaning and shape behavior (1977:12-15, 325). At the regional scale, this standpoint has formed the basis for landscape archaeology and phenomenology.

As noted above, though GIS based models are often seen as predisposed to a processual orientation (Seibert 2006: xix), the underlying archaeological concepts
contributing to the formation of the models are not by necessity mutually exclusive of one another. Understanding the contributions of each epistemological approach stabilizes landscape archaeological study within the continuum of environmental and cultural concerns (Lock and Harris 2005:42, 48). The influence of more reflexive theories combined with modern application of modeling methodologies gave rise to what Kvamme termed the “Second Age of Modeling (2005:4).”

Early Applications of Phenomenology in Landscape Archaeology

The post-processual response to the “First Age of Modeling” can be summarized as a reproach of the empirical neutrality of the processual attitude towards spatial patterning, where space is seen as an abstraction of place, having removed the personal sociocultural experiences of the people who construct it (Seibert 2006: xvii). This juxtaposition of “Space VS Place” outlined by Tilley defined space as a universal, objective, cross-cultural surface for action; where rational decision making, based on environmental factors and seasonally available resources, operated to create settlement patterns which could be plotted on maps, quantitatively analyzed, and used to discover causal spatial processes (1994:1-10). Tilley rejected this “innocent” view of space as an idealized perspective, where space existed as a backdrop or container with measureable quantities of surface and volume (1994:9). An alternate view of spaces incorporates human agency, viewing space as a subjective medium for social production which is connected to action, not separate from it. As such, the experience of space is contextual, invested with power, and is uniquely produced and realized based on relationships of gender, age, social position, and time (Tilley 1994: 9-11).
The Phenomenological approach to landscape archaeology focuses on “the manner in which people experience and understand the world (Tilley 1994: 11).” This includes both a subjective element of personal experience, and self; as well as an element of objectification by which people create and explore distance between themselves and the world they inhabit. Belief and remembrance (i.e., emotion, intentionality), decision making, action, and perception are the schema by which people relate to their existence in the world (Tilley 1994: 12). The interplay of the physical landscape and peoples’ conceptualization of it produced by the interaction of subjectivity and objectivity creates “place”, where meaning, value, and identity are expressed (Tilley 1994: 12-4). As a result, Tilley posits that the best method of studying the patterned relationships between places is through experience and observation, although admittedly a contemporary experience and understanding would differ from a prehistoric interpretation of significance of place (Tilley 1994: 74-5). Our “common biological humanity,” (i.e., the human body) mediates our interaction in the landscape, and, therefore, allows us partial access to past constructions and interpretations of the material world even though contemporaneous experience may differ (Brück 2005:47-48; Tilley 1994:74-75).

Tilley’s debut series of phenomenological case studies centered on the roles of visibility, intervisibility, and movement in the Neolithic landscapes of Wales and southern England. In each of these regions, sites occupied in the Mesolithic were formalized in location - and as Tilley argues, in cultural memory – through the construction of monumental earthworks during the Neolithic. The first of Tilley’s case studies consisted of classifying 15 Neolithic Welsh sites he had visited in the Black Mountains into four “place” categories based on topographical and ecological components of landscape.
Geological and floral/palynological data were used to inform his description of the differences between past and modern landscape features. All of the sites featured monumental stone “Cotswold-Severn” type long-cairns, and many of these sites exhibited evidence of reoccupation or occupational continuity (Tilley 1994:111-8). Tilley argued that rather than describe the orientation of the cairns as “random” (strictly in comparison with cardinal directions), their directional siting could be explained in relation to two axial orientations: those “running parallel with major rivers or their tributaries;” and those oriented “towards prominent spurs on the Black Mountains (Tilley 1994:124).” With the first group of cairns the long axis focused one’s visibility on the river valley, while the long axis of the second was aligned with spurs or terminal points of the Black Mountain escarpment edges. Tilley argued that the features used as focal points “would have been known and sedimented in social memory (1994:136, 124).” Furthermore by using the cairn chambers for burials, the “biographies of individuals” would be forever associated with those features, or places of “symbolic significance” (Tilley 1994:140).

In a study of Cranborne Chase, a chalk plateau in southern England punctuated by the remnants of earthen long barrows, Tilley again focused on Neolithic “cultural appropriation” of earlier Mesolithic sites. Measuring approximately 20-100 meters long, 12-30 meters wide, and 3-4 meters high, the white chalk barrows would have possessed a high degree of visibility and intervisibility at the time of their construction (Tilley 1994:143-158). Unlike the Black Mountain cairns, the long barrows generally ran parallel to ridge axes and landscape contours, “forming part of the landscape” rather than focusing an onlooker towards other topographic features (Tilley 1994:159-161). In addition to the barrows, crossing this landscape on a SW-NE alignment was the Dorset
Cursus – an approximately 10 kilometer long earthwork consisting of: “two parallel banks with external ditches linked together at two terminal points with crossbanks and external ditches (Tilley 1994:170).” A total of 22 barrows were located within five kilometers of the cursus, nine of which were located along its course or terminals, leading Tilley to conclude that the cursus was intentionally designed to form a nexus between them. His phenomenological investigation of these interrelated earthworks consisted of walking the two sections of the cursus and describing its path, relationships, and intervisibility with the surrounding barrows (Tilley 1994:170-84).

Walking approximately one hour along the 4.3 km long Pentridge section, the barrows were often hidden from view, and presented a surprise when encountered. By contrast, monuments within the 5.6 km Gussage section, walked in an hour and fifteen minutes, were constant and prominent presences in Tilley’s experience of the cursus, causing him to note: “these changes in the course of the cursus going up the hill do not make much impression from a map; but they would have had considerable visual impact when viewed from the Bottlebrush terminal and experienced by those walking up the cursus (Tilley 1994:188, emphasis in original).” Tilley’s interpretation of the cursus included a description of initiation ceremonies that could have taken place there. The monuments literally and figuratively restricted access and points of view, representing “a formalized structuring of the experience of landscape by those entering and using it,” and differentiating between those included and excluded from the knowledge required to derive meaning from the experience (Tilley 1994:199). Although these monuments were constructed during the Neolithic, they functioned to preserve and expound upon the social
control, ritual significance, and connection with/memory of place established in earlier times (Tilley 1994:204-5).

Owoc, also critical of the empirical objectification common in Western approaches, believed that phenomenology offers a mindfulness of alternative viewscapes which incorporate the cognitive, physical, mythical, natural, and social, with space, time, and symbolic power. By exploring a number of ethnographic examples, such as the significance of soil color to the Baruya of New Guinea, Owoc suggested that archaeologists should be aware of possible alternate categorical schemes, and of the contextual relationship between people and the landscapes they construct (2006: 4-7). This theory was applied to the study of Bronze Age funerary monuments in southwestern Britain via an experiential, practice-centered approach. Here, builders changed the appearance and shape of the mounds over time by incorporating strata of various color, texture, and consistency, creating a visible landscape feature with symbolic associations (Owoc 2006: 9-11). The taxonomy reproduced by the creation of these monuments includes a differentiation between soft/firm, dark/bright, above/below, and a temporal/vertical stratigraphic component in the meaningful construction of these sites (Owoc 2006: 11).

Like many subjects of archaeological modeling, visibility studies pre-date the use of GIS, however, their usefulness in investigating perceptual actions have led to the development of new methods of modeling the “will to visibility” in GIS. Wheatley and Gillings believe that visibility structured the configuration of culturally created landscape features, organizing past practices surrounding them. Although GIS offers a “push-button” method for binary viewshed analysis, the authors remind us of the meaning incorporated
in visibility, where the impression of a view denotes its social “effectiveness” (2000:3). After reviewing a number of pragmatic, procedural, and theoretical critiques the authors present a conceptual framework for modeling viewsheds consistent with the principles of visibility. The “Higuchi” viewshed, named for landscape planner Tadahiko Higuchi, incorporates eight indices of visibility, including the distance at which objects are perceived with clarity by the viewer (i.e., short range view) in comparison with the distance at which individual details are unclear (i.e., middle range view) (Wheatley and Gillings 2000: 14-6). In this way the placement of a burial mound within the short range view of another mound may be interpreted as highlighting direct lineage when compared to the use of a middle range view to place the ancestors in a larger temporal context (Wheatley and Gillings 2000: 18-9).

Although Wheatley and Gillings were able to incorporate one aspect of GIS modeling into an interpretive approach, it is clear that at its inception this theoretical perspective as a whole was concerned with the experience and observation of the landscape, even when it was agreed that the subjective meanings known and available to past peoples cannot be fully understood by contemporary researchers (Llobera 2012; Owoc 2006; Tilley 1994; Wheatley and Gillings 2000). In some cases, this led to a rejection of GIS modeling as a viable technique of analysis (Hacigüzeller 2012; Sui 1994; Tilley 2004, 2010:25-26), and at best created a divide between those seeking to incorporate experiential variables and the theoretical framework which inspired them (Llobera 2012; Lock and Harris 2005; Verhagen and Whitley 2012; Wheatley and Gillings 2000).
The “Second Age” of Theory in Spatial Modeling: Reactionary Processualism

In response to post-processual theories, modeling at the landscape scale underwent changes resulting in a more reflexive, yet still primarily ecologically based, second age of modeling. Given opposition to ecological/behavioral site location modeling, Kvamme (2005) posited three explanations for the continued pursuit of models:

“1. Human behavior is patterned with respect to the natural environment and to social environments created by humanity itself.

2. We know or can learn something about how people interacted with these environments by observing relationships between human residues (i.e., the archaeological record) and environmental features.

3. GIS provides a tool for mapping what we know (Kvamme 2005:6).”

Though Kvamme situated these explanations in a processual point of view, the precise interplay of these statements directly relates to how, what, and why we are modeling.

As I will return to later, the difficulty inherent in any modeling project is adopting a theoretical balance which integrates both the qualitative and quantitative; the skeptic's complex and humanized social environment, with the reductionist’s ecological landscape. Methodological innovations alone don’t constitute underlying theory, and theory without the possibility of application to a variety of datasets is impractical. I argue that GIS not
only provides a method for mapping what we know, but a method for exploring that which can be modeled (and interpreted – using a variety of interpretive frameworks). Kvamme prompted his contemporaries to consider their true goals in modeling: do we seek “to find, map and manage our planet’s cultural heritage, or are we trying to develop cultural theories of location and choice (2005:29)?” His work highlighted the importance of recognizing that modeling and theory are indeed two complementary objectives (Kvamme 2005:29).

Daly and Lock criticized a phenomenological approach for its inability to address complex multi-scalar archaeological data. They believed that structured relationships that created sites and landscape and that influenced artifact deposition and should be interpreted through social practice, revealed at five interwoven scales operating along with time (Daly and Lock 2004:352-3).

In their systematic cataloging of the intensively studied Hillforts of Ridgeway in Oxfordshire England, Daly and Lock gathered data from Later Prehistoric and Romano-British period sites (c.1000 BCE-450CE) creating a relational database which could be queried through multiple levels of scale, ranging from: object, feature, deposit, site, and landscape. Instead of emphasizing perception to uncover social practices, they searched for structured actions, in the form of repeated patterning, from which to interpret meaning (Daly and Lock 2004:353-6). Following the authors’ example, the placement of a broken tool during a fill episode in a single pit constitutes an individual action, however, the repeated finding of similar tools in other features, deposits, or at numerous sites signifies a “structured activity” to be interpreted (Daly and Lock 2004:356). By mapping the hillforts
at multiple scales, it could be determined that several Forts established on an East-West orientation were likely based on the optimal travel route and original location of the Ridgeway path. Later, when some entrances were blocked as a result of restructuring activities within the hillforts, the path was shifted; a response to the change in practice (Daly and Lock 2004:362).

In addition to modeling multi-scalar archaeological data, Kvamme suggested that researchers might also model environmental variables at both near and far scales simultaneously. In this way the variability captured in a broader regional context (e.g., rainfall data, productivity) may be applied in combination with proximal variation (e.g., slope, defensibility, accessibility) (Kvamme, 2005:31-2).

Other authors operating within the “Second Age of Modeling” suggested methods of weighting based on archaeological knowledge to incorporate elements of subjectivity without compromising the consistent application of models to different regions (Kvamme 2005; Verhagen 2005). Verhagen believed that closing the gap between qualitative and quantitative analysis may be achieved by applying Multi-criteria Decision Making, which relies on the hierarchical decisions made by the archaeologist as an expert decision maker (2005:193-8). Quantitative data were added secondarily, and only when a representative sample was available, as a way to refine the subjective weights (Verhagen 2005:200). Kvamme posits that even the selection of variables for a study requires expert knowledge based on knowledge of theory, archaeological training, and previous work. Operationally altering the relative weights of variables to create a complex model is a form
of calibration which combats the notion that statistical models are simply “correlative” in nature (Kvamme 2005:12).

Scale, spatial relationships, temporal relationships, and the application of expert knowledge are common threads which allow us to study the connections between people and the landscape. These factors are present in both processual and post processual approaches and despite the variety of ways archaeologists have approached the relationship of prehistoric cultures to regional geography we can all agree that there is meaning and value in studying them; whether eliciting social patterns imbued with power and perception or as the ecological behaviors of the human species. While the “First and Second ages of modeling” took an ecological view, it is from within these interpretive disciplines that growth, validation, and critique of modeling first occurred. To return to the words of Rapoport, “study of the elements of space, time, meaning, and communication in environmental organization is made possible due to the existence of patterned relationships between people and people, people and things, and things and other things (1977:9).”

**Tension Grows: Critiques of GIS, Phenomenology, and Quantitative vs Qualitative**

Tilley asserted that “looking at the two-dimensional plane of the modern topographic map with sites and monuments plotted on it, it is quite impossible to envisage the landscape in which these places are embedded. The representation fails, and cannot substitute for being there, being *in place*” (1994:75, emphasis in original). Although each of Tilley’s case studies described above was accompanied by maps or plans (to situate
discussion rather than provide modeling or analysis), a certain tension is apparent between his rejection of Cartesian space and his reliance on embodied presence for interpretations of place.

Daly and Lock characterize this tension as modern archaeology’s attempt “to move beyond the empirical consideration of material culture and material remains into the realms of past social practices and social reproduction (2004:362).” Lock and Harris summarize this tension by drawing upon the “GIS and Society” debate (2005:44; Curry 1998). On one hand, data are constructs, by people, for people, and as such have political, economic and sociocultural connotations. On the other, considerable amounts of qualitative data are not (or perhaps, were not yet) GIS-able, resulting in the omission of alternative ways of knowing and symbolizing this information (Lock and Harris 2005:44). Another stumbling block for archaeological GIS is what Gillings terms the “toolbox problem” or the notable propensity of GIS studies which concentrate on methodological applications with little or no underlying theory. GIS technologies were gaining popularity just as theoretical leanings shifted away from the quantitative (Gillings 2012: 603). So, who is at fault in the tension between modeling and theory, and where is the path to reconciliation?

Despite its highly cultivated theoretical reasoning (e.g., Brück 2005; Cummings & Whittle 2004; Hamilakis 2013b; Hamilakis et al. 2002; Johnson, 2012; Tilley 1994, 2004, 2008, 2010; Van Dyke 2014), phenomenological methodology has traditionally been somewhat abstract. It primarily consists of descriptive accounts of experiential archaeology, also termed subject-centered survey, where an archaeologist records and
describes their impressions of a site or feature when approached or experienced first-hand. As Stuart Eve noted, “in archaeology ‘phenomenology’ has become a loaded term,” because people claim that “…it lacks an explicit and rigorous practical methodology, is unscientific and highly subjective (2012:584).” As a derivative of this mentality, one of the primary critiques facing phenomenology is that the experiences described by archaeologists are only qualitative personal observations of individual observers, and, therefore, they offer a limited contribution to our understanding of the past (Eve 2012:585; Hamilton et al. 2006:35; Rennell 2012:511; see also Cummings & Whittle 2004; Gillings 2012; Johnson 2012; Llobera 2012; Trigg 2017; Trigger, 2006). Forbes states “the idea that one appropriates a landscape via the act of moving through it is the viewpoint of the exogenous disengaged tourist, not the native” (Forbes 2007:25). In other words, an archaeological interpretation of phenomenology has often resulted in an approach which is narrowly focused on individual experiences.

However, the “disengaged/outside individual” critique falls away when we look deeper into the foundation of phenomenological theory. Philosophical phenomenology, such as that described by Edmund Husserl, values not only individual experiences, but the way that experiences relate to one another (Eve 2012:585). By this definition, a phenomenological archaeology which incorporates a variety of methodologies and fieldwork is better equipped to explore the associations between one experience and
another, interrelations between experiences and places, and relationships present amongst multiple places within the wider landscape. What is required to move towards incorporating a variety of landscape and phenomenological approaches is a unification at the middle ground between practicable theory and modeling methodologies. The results place us somewhere between Tilley’s phenomenology (1994), which has primarily been applied to prehistoric, monumental landscapes of mid to high relief topography, and landscape modeling’s “McArchaeo Site” (Lock and Harris 2005:49; Llobera 2012). The difficulty inherent in any such study is adopting a balance which integrates both the qualitative experiential subject-centered survey data, and quantitative modeled representations (e.g., Eve 2012; Rennell 2012).

Brück noted the value of GIS and Virtual Reality modeling in phenomenology to help reveal relationships between places, and in particular symbolic links between locations (2005:52). As Llobera proposes, instead of viewing GIS as an end product, those working within an interpretive framework should view it as a resource to investigate and support hypotheses, and to develop new analytical methods (2012). All archaeologists should consider GIS a heuristic device, to be used in tandem with traditional and alternative means of depicting spatial data (Llobera 2012:497; see also Brouwer Burg 2017; Gillings 2012). As a complement to field experience and observation,

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9 These overtones are recognizable in the research questions addressed by the case studies in Chapters 7-9, which focus not only on the experience of sites as a single type of space, such as a performance space, but on the interconnection of multiple spatial experiences, such as site locations, performance spaces, and audibility from the perspective of the performer, the audience, and passive observers.
Llobera suggests that scaffolding models be developed to explore theoretical concepts in a given context. This includes models which simulate through reconstructions; determining where features co-existed; establishing criteria for comparison between locations or random datasets; contextualizing meaning and qualifying concepts, such as territoriality; recreating temporal processes; and exploring various possibilities for social action through modeling potential transformations (2012: 503-5).

Rennel’s study of Iron Age landscapes in Scotland offers a combination of visibility studies in GIS paired with subject centered field surveys, explaining that “these techniques complement one another” (2012:514). In a similar light, Eve describes the use of augmented reality as a different means of tackling phenomenological studies. His approaches span a continuum ranging from work within the real environment at one extreme, to virtual reality (or complete 3D reconstructions of the past) at the other. Augmented reality (a combination of past reconstructions and present experiences), and perceptual models, such as the Soundshed Analysis Tool, lie somewhere in between (Eve 2012). Perhaps the most important point Eve (2012) addresses are the shortcomings experienced in each of these approaches which highlight the limitations that phenomenological methodologies must seek to overcome. Admittedly, both creativity and a large number of diverse field observations are required to apply modeling to a phenomenological approach, however, the innovative application of tools, heuristics, and methods is necessary to investigate higher level questions (Llobera 2012:500, 506).

As a caveat, although this work was initially designed to achieve a phenomenological middle ground, development of the Soundshed Analysis Tool and
Archaeoacoustics Toolbox represent methodological advancements and, therefore, are not *a priori* components of any particular theoretical regime. Other interpretive frameworks, such as ecological psychology, performance theory and political theater, lend themselves to archaeoacoustics as well. These theories, related to the perception, experience, interpretation, meaning, and production of sound in the past are enumerated and discussed in detail below\(^\text{10}\).

**Recent Phenomenological Applications in Sensory Archaeology**

The phenomenological approach to landscape archaeology seeks to “break down the subject-object divide” and to “describe the character of human experience, specifically the ways in which we apprehend the material world through directed intervention in our surroundings” (Brück 2005:46). The landscape or “space” in which cultural sounds are produced is not a neutral universal container; it is a subjective medium connected to action where the social and material world convene and coalesce with the body (Tilley 1994:9-11; Van Dyke 2011:17). Space is intertwined with human agency and is thereby subject to social production and transmutation (Van Dyke 2014). The phenomenological approach is, therefore, deeply tied to sensory experience, and auditory perception is just one of many ways that people experience, find meaning, and negotiate identities in their world.

\(^{10}\) Application of these theories can be seen within the case studies found in Chapters 7-9.
Phenomenologists have long been aware of the relationship between sounds and experience (Merleau-Ponty 1962), and in landscape archaeology, the dominance of visual analysis over other sensory modalities is often noted, if not addressed (Day 2013; Hamilakis 2013b; Hamilakis et al. 2002; Ingold 2000; Mills 2004, 2014; Tilley 2008; Witmore 2006). Tilley states “surfaces, according to their direction in relation to one another, inclination, texture, and degree of absorption will structure, reduce, or amplify sound; and auditory perception derives its basis from the flow of sounds through the landscape from one place to another, producing different acoustic properties” (2008:41); however, this is where his treatment of sound ends. Prior to the middle 2010s, passing mention of acoustics remained the norm. Mlekuz (2004, discussed previously) and Hamilton et al. (2006) provide what are perhaps the earliest examples of a phenomenological milieu applied to archaeoacoustics.

In 2006, a group of phenomenologists studying soundscapes called for a clarification of the “practical methodology” associated with a perceptual/sensorial framework (Hamilton et al. 2006). Their approach incorporated various methodologies including subject centered survey which the authors believed could “enrich the scope of our thoughts questions, and understanding of the behavioral parameters concerning past site contexts (Hamilton et al. 2006:32, citing Brück 2005).” Rather than focus on monumental architecture, Hamilton et al. investigated the sounds and smells of daily life within southern Italy’s ditched Neolithic village enclosures. Today, little of these sites is extant above ground surface, which is a notable departure from phenomenology’s visually
“dramatic localized landscape” and requires use of maps and photographs typified as “the antithesis of the phenomenological experience” (Hamilton et al. 2006:35-7).

The phenomenological methods applied included: using field data sheets to record visual perceptions 360° around the viewer at “near, middle, far, and distant” scales; “flagging” the locations of subsurface structures and conducting experiments to determine effective distances for visual and auditory interaction between sites; and “phenomenological site catchment analysis” whereby a researcher walking the site recorded both the “environmental” data typical of a site catchment analysis, supplemented with impressions of landmarks and visibility while completing the journey (Hamilton et al. 2006:38-55). While investigating sound, determinations were made based upon observations in the field (unaided by acoustical instrumentation) in keeping with a traditional phenomenological approach. “Interaction” sounds were produced by both men and women and included speaking, whistling, and shouting, and gender of the perceiving individuals was noted. “Everyday” sounds and smells including those of horses, dogs, sheep bells, meat cooking, children playing, a crying baby, and close conversation were also investigated (Hamilton et al. 2006:47-52). This seminal work not only laid the foundation for phenomenological methodologies, it included a basic consideration of speech transmission and audibility at the landscape scale. Researchers have since employed acoustical standards, computer simulation, and modeling to continue this line of exploration as described in the previous chapter (e.g., Boren 2014, 2016; Boren et al. 2013, Villanueva-Rivera et al. 2011).
Applying both Phenomenological theory and archaeological evidence from the Chacoan archaeology of the Southwestern US, Van Dyke employed a series of “imagined narratives” to elucidate new research questions and thwart some of the criticisms of phenomenological research outlined above. These “creative nonfictions” allowed the author to investigate a person’s perception and experience by incorporating age, gender, ethnicity, roles, and status (Van Dyke 2013:390). From the perspective of a 10 year old girl, Van Dyke describes the four day journey from an outlying community to the great house at Peñasco Blanco. Rather than focusing exclusively on what landforms were visible, she also describes the “traveling activities” that take place as well: storytelling, visiting family while on route, fatigue, singing, and sharing meals. The narrative concludes with the group’s arrival:

“On the fourth day of our journey, we walk east up the Chaco Wash from the great house of Casa del Rio toward West Mesa. In the distance, I see a row of watchers standing atop the mesa edge, silhouetted against the sky . . . but as we move nearer I can see that these are not people, but shrines. My heart pounds with excitement. Chaco, at last! We round the edge of the mesa and enter the canyon, and suddenly we are assaulted by a cacophony of drumming and singing, barking dogs, and babbling voices..... (Van Dyke 2013:390-1).”

Following the narrative, Van Dyke cites and describes several pages of archaeological evidence gathered over a century which contributed to the “account,” and notes that the inclusion of such representational prose in scholarly work is itself a rejection
of Western, Cartesian categorical separation of emotional and analytical sensibilities (2013:391-6). She argues that whether through such narratives, or by subjectless descriptions, archaeologists are still “speaking for past peoples,” albeit this is readily apparent through prose (Van Dyke 2013:397-8). Working with the narratives as a foundation, Van Dyke concludes by outlining exiting issues and new research questions identified through the phenomenological approach (2013:400, Table 19-1).

Taking a more holistic theoretical approach, for Hamilakis, sensory experiences are not just synesthetic, but include elements of movement (kinesthesia) as well (2013b:114). Sensory flows “involving things, environments, and other beings” continually affect the body resulting in a reflexive engagement that is greater than the sum of mechanical “instrumentalization of the senses” and human biology (Hamilakis 2013b:116). Flows include sound waves, odors, memories, ideas, substances, and other tangible and intangible elements which may coalesce unpredictably in sensory experience.

Similar to Van Dyke, Hamilakis combines “academic essay and storytelling” in his sensory archaeology of Bronze Age mortuary practice on Crete (2013b:117, 130). During the Pre- and Proto-Palatial periods (c.3100-1700 BCE) the dead in south-central Crete were interred in monumental circular vaulted tholos tombs constructed of stone. Tombs were communal and used repetitively, marking them as places of memory and gathering for centuries (Hamilakis 2013b:130-2). Describing one’s visit to the tomb as part of a funerary rite, Hamilakis states:
“Darkness, lack of space for movement, and, above all perhaps, the strong odour of decomposing flesh, amplified by the enclosed, hemispherical space, transports you to a realm both spatially and temporally distinct, and markedly different from that of the everyday. Yet, you have been here before. The smell is familiar; the flickering light of the lamp aids the recognition of the micro-regions of the tomb. In some cases, you can even recognise [sic] distinctive objects, peculiar stone and clay vessels, and the odd sealstone, metal dagger, or marble figurine. You recall persons long dead, you start making associations; you connect bones, skulls, and objects with times, places, living humans (2013b:134).”

The narrative continues, describing the sensorial assemblage comprised of odors, ceremonies, eating and drinking, dancing and music, intoxication and the use of psychoactive substances, and the use of rare and unusual objects in association with the funeral. After a time, the corpse decomposed or had remaining flesh and clothing burned away, making the temporal transition from individual social agent to ancestor. Following this transition, the disarticulated remains were piled collectively, making physical and social space for the inhumation of the more recently deceased. For those taking part in the burials, engaging with mortuary spaces through embodied sensorial practice results in the creation of “deep maps,” the mnemonics of which were accessed through movement and the spatio-temporal “props” of funerary items (Hamilakis 2013b:134-8, 157-60).
However, as explained previously in this chapter, there remains a tension between Tilley’s phenomenology and GIS applications. While the case studies reviewed in this section are prime examples of applications of Phenomenological theory to sensory archaeology, there are some researchers who believe that finding “the middle ground” is simply put, a “lost cause” and that effort could be made elsewhere.

**Ecological Psychology (Affordance Theory) in Sensory Archaeology**

“Ancient stones in landscapes…cannot be known or understood simply from publications, from maps, diagrams, photographs, and descriptions because these are only representations… Statistical analysis, Geographical Information Systems and simulations are, if anything, far worse. There can be no substitute for the human experience of place – of being there – and it is only after this that the various technologies of representation come into play (Tilley 2004:218).”

Reading this, many researchers working with GIS or other spatial representations or models, including Gillings (2012), abandoned phenomenology and sought alternative perceptual theories.

In pursuing an archaeology of the senses what we are truly applying are philosophies of perception and theories of agency. Within each perceptual theory, agency lies with one or several disparate individuals or groups. This is illustrated by Ingold’s (2000) comparison of several philosopher’s treatments of visual perception. Notably, Ingold compares the works of both ecological psychology’s James Gibson and
phenomenology’s Maurice Merleau-Ponty, grounding both in comparisons with Descartes.

As described by Ingold, Descartes, and others before him, viewed visual perception as a two part process: the eye perceives an object through light and that light is interpreted in the mind through nervous impulses\(^\text{11}\). This position forms the basis for Ingold’s comparisons (2000:254-7). Gibson’s conception of visual perception is that it occurs directly as the result of an organism exploring its environment, rather than as a “computational activity of a mind within a body (2000:260).” Like Descartes, Gibson places an emphasis on movement of the body, and for Gibson visual perception also included sensations derived from hearing and touch.

As Ingold summarizes, Merleau-Ponty’s description of visual perception also includes movement and integrated sensory input, while acknowledging that individual senses are differently structured. However, in a point of departure from Gibson, for whom vision takes place through identifying affordances in the environment, Merleau-Ponty describes vision as occurring in the outside world, thus the indistinction between “sensor and the sensible” (Merleau-Ponty 1962). Thus, for Ingold these philosophies represent vision as modes of speculation, participation, and being, respectively (2000:262-5).

\(^{11}\) Note that for Descartes the first step in visual perception does not rely exclusively on light. He provides an example of a blind man using a stick to judge the distance between two objects, therefore, for Descartes perception occurs in the second stage of the process and is tied with the importance of movement in relation to the objects perceived (Ingold 2000:254-5).
In Gibson’s “ecological psychology,” often referred to as “affordance theory” by archaeologists, an importance is placed on the visual perception of the unique combination of substances and surfaces from which a person or animal perceives value and meaning; that is, what the environment offers or “affords” us. In simpler terms, using their senses the observer immediately perceives how the environment may be used to suit their purposes. Affordances cannot be reduced to the qualities that the environment or objects may possess (e.g., mass, size, shape, color, and texture), they are “invariant combinations” of the substantial, and of the geometric layout of surfaces. For example, when a substance is level, extended, rigid, and flat, the collective perception of those traits indicates that the surface is “stand-on-able,” or “walk-on-able;” when these traits occur within an object at approximately knee height, then the object affords “sitting on” (Gibson 1977:67-8, 75). These properties that describe the floor, ground, bench, or chair are a collection of variables that are not evaluated in isolation from one another. A similar evaluation of affordances occurs when an observer perceives objects “detached” from the environment (i.e., “things” or artifacts that may be manipulated), and during social interactions with other people, to which Gibson attributes the same standards of perception or misperception as one would use to evaluate any “detached objects” in the environment (1977:68-9, 75-6).

Similar to a phenomenological perspective, affordance theory rejects the subjective-objective dichotomy, however, Gibson’s theory also dispenses with the separation of the phenomenal world of the mind from the physical world of matter
(1977:77). For Gibson, human manipulation of the environment\textsuperscript{12} occurs to provide new affordances. Affordances may also be simultaneously positive or negative; for example, fires “afford being warmed and being burned” (1977:76).

In an early application of affordance theory, Llobera combined Giddens’ concept of “rules”, Bourdieu’s concept of “habitus”, and Gibson’s concepts of “affordance” and “niche” to theorize how dispositions inform practices and explore these concepts through GIS (Llobera 1996:614 citing Bourdieu 1977; Gibson 1986; Giddens 1984). Building on a case study by Bradley et al. (1994) of Late Bronze Age linear ditches in Southern England’s chalk downs, Llobera refutes the authors’ conclusion that the ditches were territorial markers meant to enclose spaces. Based on GIS analysis Llobera instead proposes the ditches appear to be defining dichotomous “linearities”, splitting or compartmentalizing the landscape on either side but not enclosing it (1996:615-9). This leads to the conclusion that the divisions were organizational in nature, such as mile markers, rather than demarcations of territorial hegemony (Llobera 1996:620).

Llobera’s pioneering early work received criticism, notably that of Webster who asserted that abilities differ between individual people leading to differing affordances, however, Webster also stated that these affordances are perceived internally, within the mind, therefore, he concluded that Llobera’s work fell short of a Gibsonian study (Webster

\textsuperscript{12} It is important to note that for Gibson, there is only a singular “environment” comprised of both the “natural environment” and any anthropogenic modifications. “Cultural” environment is, therefore, an invalid term. (1977:70).
Gillings notes the common impediment observable in Webster’s reading of Gibson (2012:604-5). By adopting a “dispositional” reading of Gibson, Webster and others of this persuasion place an emphasis on actualizing circumstances in which affordances may be perceived – in Websters’s case, as in others’, this is relative to body scale and the emphasis is placed on the animal’s perception rather than features of the environment (Chemero 2003:183-4; Gillings 2012:605). However, affordances lie neither within the environment, nor within the minds of animals, but in the relationship between features of the environment and the abilities of animals. Chemero (2003) provides an excellent summary of both the selectionist and dispositional viewpoints, as well as a detailed explanation of the relationist view. In his review, Chemero responds to the question implied by Webster’s critique, “do affordances exist without animals (2003:193)?” Chemero answers this question using Dennett’s (1998) description of things that are “lovely” to illustrate; things that are lovely, such as a flower, remain lovely even in the absence of an observer. Therefore, affordances will exist in which a situational feature participates “as long as some animal exists with the appropriate ability”… “to perceive and take advantage of them (Chemero 2003:193).” Taking this explanation one step further, affordances are, therefore, GIS-able because they are real entities and don’t rely on the presence of a person to perceive them.

13 An alternative reading of Gibson is the “selectionist” view, whereby selection pressure gives way to animals developing perceptual systems to recognize resources (i.e., affordances). In this reading of Gibson, affordances are latent properties of the environment which can be perceived (Chemero 2003:181-3).
Spatial technologies when taken together with affordance theory become heuristic devices for investigating experience. Considering the hypothesis that it was important for Neolithic monuments in France to be placed in locations with ocean views, Gillings used GIS to create a number of viewsheds, then he used that data to create a layer describing the total seascape area visible from important viewpoints. The exploration of affordances lied not in the data, but in using the data to “think out loud” about the relationship between people and the view the landscape afforded (Gillings 2012:608-9). Similarly, Gillings used GIS derived “potential flood zone” maps to explore what floods afforded farming communities in Neolithic Hungary. His consideration began with mapped data but went on to include discussion of the perspective of various members of the community (e.g., an adult vs. a child) (Gillings 2012:609). This study only delineated the boundaries of what Gillings termed a “sensory envelope” regarding the experience of a flood, that is, physical limits of where the sights, sounds, smells and other sensory information associated with a flood “might be expected to be actively recognized (2012:609).” However, by defining these areas he creates an exploratory framework for investigating the affordances and experiences of quotidian life.

Focusing on sounds, Mills describes “place” in auditory terms as “the complexity of the composition/matrix/tapestry” of a location comprised of “interwoven threads” of information (2005:80). Mills’ work studying the 5th millennium BCE Teleorman River-Valley in Romania focuses on what was heard in daily life, i.e., sounds of practice, which actively or passively created auditory information that was fundamental in shaping social relations. Mills’ “auditory scene analysis” ties sound to the environment at large, much as
Gibson’s affordances rely on visual observations to do the same. Whereas visibility may offer an expansive vista or still frame, as would a photograph, and therefore, offer associated impressions of timelessness, auditory perception is dynamic by its very nature, requiring something to be vibrating or happening to create the sound (Mills 2005:81).

Like affordances, auditory scenes are perceived and analyzed as collectives of known variables allowing inhabitants to “engage knowledgably with their surroundings” and understand what resources the particular environment affords them. This understanding is implicit and often subconscious, learned over time through embodiment, and allowing the potential for acoustic information to become ensconced within identity (Mills 2005:86). Mills 10 x 10km study area in Romania presently remains rural agropastoral and also exhibits stable landforms and ecology, allowing him to use modern acoustical data in studying auditory character areas from the past. A series of georeferenced recording stations were placed within a variety of topographic, ecological, and human activity areas, and three character areas were defined based on the acoustical data collected: the eastern valley/edge meadow zone, the open valley floor/grassland zone, and the river zone (Mills 2005:84-5). In the eastern valley edge, for example, the propinquity of animals and permanent human dwellings created a dynamic and lively polyphony which signals “a sense of belonging through co-presence (Mills 2005:85).” By contrast the grassland zone was often only occupied by herders, their animals, and birds, resulting in homophonic acoustics typically dominated by a single source and bestowing a “sense of isolation (Mills 2005:85).” In their daily lives people
would move through such scenes and identify with those sounds related to the resources which they associate or expend, such as the shepherd and the sounds of their flock.

Departing from Gibson’s visually based engagement with the environment, Mills focuses on auditory archaeology, proposing four “key principles” to acoustic study: 1. it is about interrelationships and variation over time and space between people, places, materials, activities, and sounds; 2. sound is ecologically structured, encoded with environmental information; 3. The human body processes acoustic information as a whole; 4. Decoding acoustic information does not need to be an active process, and in fact familiar or recurring sounds contribute to one’s sense of “place” (Mills 2004:3, 2014:76). However, despite the well-established principles, Mills cautions that no mode of sensory engagement, including hearing, should be advanced over other means of embodied understanding (2014:79).

While some, like Gillings (2012) have considered ecological psychology as an antithesis to a phenomenological perspective, others such as Halona Young-Wolfe believe that the two theories are complementary. The incorporation of affordance theory addresses many of the major critiques to phenomenology – most notably the western world’s tendency to place emphasis on the symbolic or idealized “final product” and to privilege subject over object despite phenomenologists’ stated rejection of Cartesian separation of the two (Young-Wolfe 2015:149-52). Young-Wolfe steps away from Tilley’s version of phenomenology preferring instead Heidegger’s phenomenological theory which focuses more on the “interconnectedness of people and objects” (2015:154). Heidegger’s definition of the functionality of equipment, or “that which makes the thing
what it is” is similar to Gibsonian affordances, and together these theories consider the human element inseparable from the greater environment, where people and environment are in relation with objects that are functioning as active components of direct perception. Embodiment can, therefore, be defined by this intermingled relation where interaction through affordances results in shaping of and by the environment (Young-Wolfe 2015:155-7).

As an example, Young-Wolfe considers the use of certain quotidian objects, *shicra* (bagged fill) in the construction of Late Archaic (c. 3000-1800 BCE) Peruvian monuments. While others have focused on the emerging monumentality of this era, she asks how the monumental structures “fit into people’s lives (Young-Wolfe 2015:160-4, 168).” The study of *shicra* is offered as a glimpse of daily lived experience. At their simplest, *shicra* afford containment and are used primarily to hold large stones, although variations held sand and other fill-related objects. *Shicra* were made from a particular species of strong sedge that afforded both weaving/braiding, and seasonal harvesting. Other objects of daily life were also made from these sedges, including baskets, bags, and multipurpose mats used for roofing, flooring, and the burial of the dead (Young-Wolfe 2015:164-6). The skillset required for constructing *shicra* was also used for creating cotton fishing nets, though *shicra* required cooperative creation as one person would have filled the *shicra* while another was busy weaving (Young-Wolfe 2015:166-8). Though placed with the monuments, Young-Wolfe concluded the *shicra* were not essential to their construction and were, therefore, more likely to be placed based on existing/past traditions of material culture.
Given a more traditional interpretation of phenomenology as promulgated by Heidegger (1982) and Merleau-Ponty (1962), and Chemero’s (2003) detailed explanation of the relationships central to affordance theory it is evident that these theories can and do complement one another particularly when applied to studies of everyday life. Other theories related to ecological psychology, such as Hodder’s entanglement theory (2012, 2016) which studies the relationships between humans and things, might also provide an appropriate theoretical approach to archaeoacoustics in connection with affordance theory or in its own right.

**Performance Theory and Political Theater in Sensory Archaeology**

While phenomenology focuses on the experience of the individual in their negotiation of identities and meaning, performance theory and political theater rely heavily on the use of interpersonal interactions and a group dynamic to achieve the same. In particular these theories are predicated upon the relationship between individuals, one and many, or few and many; where the individual, one or few participants constitute the “performers,” and the many participants compose the “audience.”

The theory of “Presentation of Self” derives from the work of Goffman, who believes that when a person interacts with others, even on an informal or day-to-day basis, they will “have many motives” for controlling perceptions of that interaction (1958:8). This does not imply conscious awareness of the adoption of a “front”, a measure of calculation on behalf of the performer, or even intentionality, (though these certainly do occur); rather, Goffman focuses primarily on the influence resulting from the interaction.
This can be seen in his definition of performance: “all the activity of an individual which occurs during a period marked by his continuous presence before a particular set of observers and which has some influence on the observers” (Goffman 1958:13). Following this, a series of repeat performances by that individual gives rise to an idealized “social role” “…thus when the individual presents himself before others, his performance will tend to incorporate and exemplify the officially accredited values of the society, more so, in fact, than does his behavior as a whole (Goffman 1958:8, 22-3).” When intentionality appears in performance, it is used to communicate idealized relationships, emphasizing a connection between the performer and audience, or implying that the current enactment is the performer’s most essential function (Goffman 1958:30-1). Though not an archaeologist, the influence of Goffman’s ideas are apparent in both performance theory, and political theater where perceptions are driven by social interaction, values within a cultures, and formal or informal hierarchies.

Hymes described performance as “something creative, realized, achieved, even transcendent of the ordinary course of events” that members of a culture could interpret, report, and repeat (1975:13-4). He posited a series of questions for investigating cultural behavior as performance including: “what behavior is interpretable (cultural?) in this community? for this person? what behavior is reportable in this community? by this person? what behavior is voluntarily doable in this community? by this person? (1975:15)”

14 In a truncated definition of performance appearing in his introduction, Goffman interchangeably uses the term “participants” in place of “observers” and further introduces the terms “audience” and “co-participants” (1958:8).
While Hymes had the benefit of working directly alongside living members of the communities he was investigating, his theoretical contributions and questions have been adapted to archaeological applications by researchers such as Inomata and Coben.

Inomata and Coben (2006) adopted Hymes’ definition, which incorporates daily practice, in their own description of performance, and included definitions of theatricality, spectacle, and other components of more formalized performances in their work. Performance is further defined as “events involving multiple individuals or groups which form a process and arena of political and ideological negotiation, competition, and collaboration” and Inomata and Coben intimately link performance to the growth and advancement of centralized polities (2006:11-2). Performance is, therefore, not only a mode of interaction tied to morals and identity, but can be used to develop and strengthen asymmetrical power relations, often in a circuitous manner (Inomata and Coben 2006:12). Theatricality, a feature of formalized or ritualized performance, provides the audience with more than the role of observers: the audience may also evaluate and participate in the performance to varying degrees; and provide emotional responses or feedback to the performers (who may simultaneously undertake an audience role themselves). Theatricality includes varying degrees of symbolic reality as well as the use of “material images in dynamic motion” (i.e., props or other representations) produced or manipulated by the human body (Inomata and Coben 2006:15).

Spectacles are one type of theatrical event, defined as a group gathering featuring a performance “in which participants witness and sense the presence of others and share a certain experience (Inomata and Coben 2006:16).” This definition encompasses a
variety of ceremonies and rituals, including: public address, sporting events, and even ritual sacrifice or execution. Spectacles often occur in association with monumental architecture or features, which by their contrast to quotidian structures can “mediate the construction and negotiation of the meaning associated with landscape and time,” providing a stage or “ordered space” for the definition of social relations (Inomata and Coben 2006:16-7). It is this active (and potentially “highly conscious” or intentionally manipulated) creation of cognitive models which provide performances, spectacles, theatricality, and audience participation with the ability to forge and affirm political authority and power relations through collective identities (Inomata and Coben 2006:19-25).

In an application of performance theory to Andean funerary processions, Moore described the symbolism and formality accompanying the spectacle of the procession as a connection between the sacred and the ritual, where the ritual employs “more restricted and defined codes of verbal and nonverbal communications than “ordinary” behavior: for example, stylized speech, verbal tones, gesture, etiquette, and attire (2006:56).” In addition, while instruments such as flutes, pipes, bells, rattles, conch shell trumpets and drums featured in a variety of Andean public performances including processions, fiestas, and taquis (communal musical celebrations), ethnographic and archaeological evidence revealed various soundscapes accompanying disparate segments of the funeral ceremony. For example, Inka funeral processions included offerings and weeping, but were not accompanied by drums, however, when Inka mummies were exhumed for subsequent celebrations, drums were played to honor the dead (Moore 2006:62-8).
Moore suggests that the act of drumming was one of the factors which delineated classes of mortuary spectacle (Moore 2006:72).

Critical of the daily “maneuvering” that Goffman termed performance, Houston referencing Beeman, defines performance as “a ‘marked’ behavior of restricted occurrence (Houston 2006:138 citing Beeman 1993:377).” He further differentiates between performance, ritual, and spectacle, defining the latter as “inherently staged, and achieves greater intensity by introducing a welter of central and marginal activities and central and marginal people (Houston 2006:138-9).” Spectacles are then subdivided into those with uncertain outcomes (e.g., games, sport, war), those with certain but nondirectional outcomes (e.g., weddings, rituals, feasts, monument construction), and those with certain, directional outcomes (e.g., processions, parades). In applying his definitions to Classic Maya dance, Houston noted that the Maya concept of self also entered into performance and spectacle. For the Classic Maya, the self could consist of a concurrent occupation of the body by an individual and a deific “guest,” whereby the dancer is the deity they impersonate (Houston 2006:144-6). Ethnohistorical accounts of Colonial period Maya dancers support this view stating “most of the Indians who take part in this dance are superstitious about what they have done, and they seem almost to believe that they have actually done what they only performed for the dance (Inomata 2006:196 citing Gage 1958:246-7).” Dances were accompanied by song and sound as well as by censor smoke which contributed to both smell, and the visual effect of deities floating, appearing, or disappearing suddenly (Houston 2006:142-3).
While archaeological evidence of Classic Maya production and trade exhibits a tendency towards decentralization, preparation, arrangement, and implementation of dances and other spectacles brought citizens of a polity together. Classic Maya dances and other spectacles took place in a variety of settings, including plazas, building steps, temporary scaffolding or stages, and dance platforms. When performed by elites, these spectacles were employed as binding forces among the attending audience, helping to “ground precarious community identities on sensible physical forms through the use of symbolic acts and objects (Inomata 2006:197-206).” Spectacles served to express ideologies, maintain asymmetrical rule, and were also considerable economic events in addition to their entertainment value. Once institutionalized, spectacles generally enhanced elite power by maintaining these inequitable relationships, however, increased ceremonialism also restricted the power of individual elites by placing emphasis on the tradition of kingship rather than individual kings. This resulted in a dynamic of power negotiations through public performance (Inomata 2006:210-11).

Both Houston and Inomata identified the importance of dance and political spectacle in Classic Maya society. Through managing performance, including what was said and heard, elites could control and influence perception. Similarly, by ascribing symbolism while controlling the associated soundshed within Andean mortuary ritual as described by Moore, an impression of the sacred could be engendered.

In contrast to ecological psychology which is suited to studying all relations between people, environment, and objects including the mundane (e.g., Young-Wolfe 2015), the application of performance theory and political theater are best suited to
studies which include heavily symbolic or idealized spectacles, monumental architecture, and meanings. When possible, these theoretical approaches can benefit from inclusions of ethnographic study or analogy (Howes 2008; Hymes 1975; Inomata 2006; Kolar 2013, 2017; Kolar et al. 2018; Moore 2006). For example, Howes suggests utilization of a tripartite approach: “(1) observing the sensory characteristics of a culture, (2) understanding those sensory characteristics in their own cultural context, and (3) interpreting and analyzing the collected material in a broader cultural... perspective” (Howes 2008:445). Incorporation of an *emic* perspective whenever possible is further supported by statements such as Valk and Sävborg’s: “the relationship that people develop with locality, the belief systems and narrative theologies they share – and their very place in the world is thus unique, and differs from that of neighboring communities” (Valk and Sävborg 2018:8). When applying this to ethnographic data, the *emic* perspective may be memorialized in regional legends (Valk & Sävborg 2018).

**Discussion**

As Scarre notes, archaeoacoustics is an integral method for understanding the lived experience of past people (Scarre 2006), and, therefore, researchers should not limit its applications based on traditional theoretical leanings. This chapter has provided a brief overview of the tension between processual and post processual theories, and the related quantitative and qualitative aspects of studying sensory archaeology via GIS. Though there is some degree of discord regarding theoretical applications in archaeoacoustics, this summary provides examples through case studies of the varying hypotheses these theories can produce and explore.
Dobres and Robb state, “Importantly, a case study is not the application of theory to the archaeological record. The reason good case studies move the discipline forward is not just because they apply some abstract theory to a material pattern, but because they suggest new ways to see and make sense of that pattern (2005:161-162).” Accordingly, Chapters Seven, Eight, and Nine apply a variety of theories in different combinations based on the hypotheses driving each study. phenomenology appears in both Chapters Seven and Nine, studies at Chaco Canyon and in Ireland respectively, while performance theory can be seen in both Chapters Seven and Eight (a case study at Copan). The *emic* perspective is captured in the study from Ireland, and ecological psychology or affordance theory is applied in Chapter Nine.
Chapter 4. Acoustics and Sound Physics, Hearing and Perception

Sound behaves predictably according to established physical laws, therefore, sound lends itself to being modeled both in present and past scenarios. However, despite the objective, predictable, and distinctively reliable nature of acoustic science, the perception of sound is by contrast enveloped in subjectivity and the perception of the listener. To better understand this interplay of the objective and subjective we must begin by exploring how sound travels through the landscape.¹⁵ To do this I will first review some basic principles of sound physics, focusing primarily on those related to outdoor sound propagation and the functionality of the Soundshed Analysis Tool, followed by a reviewing a selection of national and international acoustical standards which have some application to archaeoacoustical study. Next, I will turn to a discussion of perception, psychoacoustics and the importance of including the anthropological perspective.

**Acoustic Science: An Introduction to the Physics of Outdoor Sound Propagation**

Acoustic science states “a sound is said to exist if a disturbance propagated through an elastic material causes an alteration in pressure or a displacement of the particles of the material which can be detected by a person or by an instrument (Beranek and Mellow 2012:5).” More simply stated, sound spreads following the basic laws

¹⁵ Note that although several sound physics formulae and acoustic engineering standards are discussed, the information presented here is not intended to be a comprehensive review of acoustical mathematics and the variables effecting sound; rather, it centers on the principals of environmental acoustics and the propagation of sound outdoors as related to archaeological landscapes.
governing waves and particle dispersion. For archaeoacoustical purposes, the elastic material that sound waves traverse is air. When pressure is applied to the air, compression occurs, particles move and collide transferring momentum. If the pressure is reversed, rarefaction occurs and air particles move backward. When this process is repeated a sound wave develops (Beranek 1993:5-6).

**Figure 4.1. Schematic of a Soundwave**

![Figure 4.1. Schematic of a Soundwave](image)

Figure 4.1, above, shows an idealized sinusoidal plane wave representing a tone of a single frequency, such as one produced by a musical instrument. In Figure 4.1
compression is occurring when the wave travels above the horizontal line, and rarefaction is occurring when it dips below it. At each point where the horizontal line is crossed the particles are at their zero or resting position.

As seen in Figure 4.2, below, particle displacement and pressure are 90° out of phase with one another, therefore, where particle displacement is maximum, pressure is zero. Even though particles are moving at the same frequency as the vibration source,

**Figure 4.2. Wave Pressure and Particle Displacement**
transmission doesn’t occur instantaneously (i.e., at the same time), therefore, as the distance from the source increases there is also an increased delay in the arrival of the sound. A wavelength is defined as two points along the wave that are vibrating in phase (see the start and end points of the idealized wave in Figure 4.1) (Beranek 1993:5-7). This relationship between wavelength, frequency, and the speed of sound can also be described as follows:

“A wavelength is equal to the speed of propagation divided by the frequency of vibration.

\[ \lambda = \frac{c}{f} \]

Where: \( \lambda \) = wavelength in meters (or feet)  
\( c \) = propagation of the sound wave in meters (or feet) per second  
\( f \) = frequency in cycles per second [Hertz]. (Beranek 1993:7)”

(Equation 1.1)

This can also be written as

\[ c = \lambda f \]

(Eq. 1.2)

to show the inverse relationship between wavelength and frequency – that is, as one decreases the other increases (Cowan 1994:7).

During the propagation of a soundwave, particles accelerate longitudinally, and temperature and pressure oscillate. Excess pressure, or “sound pressure,” defined as
“the incremental variation in pressure above and below atmospheric pressure” is the property of sound that is most indicative of audibility (Beranek 1971:1, 1993:8). Sound pressure is typically measured in decibels (symbolized as dB), and the use of the term “level” indicates that it is a logarithmic ratio (Cowan 1994:31).

“The Sound Pressure Level (SPL) of a sound in decibels is 20 times the logarithm to the base 10 of the ratio of the measured effective sound pressure of this sound \(p\) to a reference effective sound pressure \(p_{ref}\),” or

\[
\text{SPL} = 20 \log_{10} \frac{p}{p_{\text{ref}}} \text{ dB}
\]

Where: \(p_{\text{ref}} = 0.0002\) microbar \((2 \times 10^{-5}\) newton/m\(^2\)) (Beranek 1993:13)

(Eq. 2)

The temperature of the air or other medium that sound pressure waves are travelling through determines the speed of sound; for example, sound travels at 344.8 m/s \((1131.2\) ft./s) at a temperature of 22º C \((71.6º\) F) and would travel slower in cooler temperatures. The speed of sound in air can be calculated using the formulae:

\[
c = 331.4 + 0.607\theta \text{ \ for m/sec \ where } \theta = ^\circ \text{C}
\]

(Eq. 3.1)

Or \(c = 1052 + 1.106F\) \text{ \ for ft/sec \ where } F = ^\circ \text{F}

(Eq. 3.2)
“For temperatures above 30º C or below 30º C, the velocity of sound must be determined from the exact formula:

\[ c = 331.4 \sqrt{\frac{T}{273}} = 331.4 \sqrt{1 + \frac{\theta}{273}} \]

Where: \( T \) = ambient temperature in degrees Kelvin" (Beranek 1993:10)

(Eq. 3.3)

Unlike the idealized one-dimensional plane wave discussed previously, sounds occurring in the landscape radiate spherically where no reflecting surfaces are present, just as a pebble dropped in a pool of water will create spherical ripples. The Soundshed Analysis Tool as discussed in this dissertation models the spread of sound of a spherical non-directive\textsuperscript{16} source or “point source.” Sound propagation is physically similar to light propagation, although the human sensory organs perceive the parameters of these phenomena differently. Whereas light is typically described using its wavelength, sound is described based on its frequency (Cowan 1994:4, 9). For a sound to be heard by people, its component frequencies must range from approximately 20 to 20,000 cycles per second (Hertz, or Hz). Most dominant frequencies of speech, however, range from 500 to 2000 Hz (Cowan 1994:5; Lamancusa 2001; Lord et al. 1980:5). Sounds can be described either by referencing their dominant frequency or through spectrum analysis, of which octave band analysis is the most common form. Frequency bands are divided

\textsuperscript{16} Sound spreading losses for directional sources can be calculated by including the directivity index in the SPL calculations. See Rossing 2007:115 for more information.
logarithmically and identified by their central logarithmic values, where each central value is twice the frequency of that below it (Cowan 994:38).

Just like light, sound is susceptible to reflection, refraction, diffraction and diffusion. Reflection “occurs when sound waves bounce off a surface at the same angle, with respect to a line perpendicular to the surface, at which the sound was incident on the surface (Cowan 1994:9).” Refraction follows Snell’s law, whereby “sound will change direction when traveling into a medium that conducts sound at a different speed (Cowan 1994:11).” Refraction can also occur when sound passes through areas of the same medium experiencing different conditions (e.g., temperature, wind, humidity). Refraction results in a bending of sound waves (Cowan 1994:9-11). Snell’s law is expressed mathematically as:

\[ \frac{c_2}{c_1} = \frac{\sin \theta_t}{\sin \theta_i} \]

Where:
- \( c_2 \) = speed of sound in the transmitting medium
- \( c_1 \) = speed of sound in the incident medium
- \( \theta_t \) = angle of transmission*
- \( \theta_i \) = angle of incidence*

* with respect to the line perpendicular to the medium interface

(Eq. 4)

Diffraction occurs when sound waves bend around a partial barrier, and diffusion caused by reflection off of uneven or convex surfaces, results in sound spreading evenly (Cowan 1994:11). As will be discussed further in the next chapter, the Soundshead Analysis Tool and the “Variable Cover” tool model diffraction (i.e., barrier attenuation,
vegetation attenuation) in addition to other acoustical phenomena affecting the spread of sound in a free field.  

When working with the acoustics of the landscape, the conditions of concern occur within two measuring environments or "sound fields:" near field, and far field. Sound levels within the near field, defined as “within one-quarter of the largest wavelength of interest” from the sound source, can vary substantially (±10 dB), particularly if reflective surfaces are present within the near field environment (Cowan 1994:63). For this reason use of sound level meters within the near field can provide skewed results due to artificial amplification or incoherent sources. Beyond the near field is the aptly termed “far field” where sound spreads predictably and sound levels recorded with a meter are subject to significantly less variation (Cowan 1994:63). While the relationship between frequency, wavelength, and the speed of sound remain the same in a spherical sine wave, the sound pressure amplitude becomes dependent on distance (Beranek 1971:14-15). This decrease of sound pressure over distance is referred to as “Distance Attenuation” which is calculated according to the Inverse Square Law (see Equation 5, below). This law states that sound pressure falls “as the reciprocal of the square of the distance from the source” or at an approximate rate of 6 dB as the distance from the source doubles (Cowan 1994:274).

17 As indicated in the studies reviewed in Chapter 2, sound propagation in enclosed or partially enclosed spaces (e.g., caves) is also subject to additional phenomena such as reverberation, resonance, and echoes, which are not discussed here. For more on these topics refer to Cowan 1994 pages 13-19.
Distance attenuation may be expressed mathematically as:

\[ dL = L_{p2} - L_{p1} \]

\[ = 10 \log (R_2/R_1)^2 \]

\[ = 20 \log (R_2/R_1) \]

Where:
- \( dL \) = difference in sound pressure level (dB)
- \( L_{p1} \) = sound pressure level at location 1 (dB)
- \( L_{p2} \) = sound pressure level at location 2 (dB)
- \( R_1 \) = distance from source to location 1
- \( R_2 \) = distance from source to location 2

(Eq. 5)

The far field can also be called the “direct field,” a term which implies that measurements “are indicative of those generated only by the source of interest, without the contributions of reflections that would add to the measured level;” or a “free field” which specifies that there “are no obstructing surfaces in the sound path of spherical wave propagation,” i.e., outdoors (Cowan 1994:64). When discussing the results generated using the Soundshed Analysis Tool the term free field is used most often, however, use of the term “direct field” would also be accurate.

As sound travels away from the source, it is also subject to atmospheric absorption. Air disperses sound via two primary means including a combination of absorption and radiation called “relaxational processes,” and by heat loss due to friction. Air temperature, relative humidity, atmospheric pressure and the frequency of the sound all factor in to the air attenuation coefficient, as do the relaxation effects on Oxygen and
Nitrogen at the given percentage of relative humidity (Lamancusa 2009:10.3; Rossing 2007:116). Atmospheric Absorption can be calculated using the following equations (per ANSI 1995:3; ISO 1993:3; Lamancusa 2009:10.3; Rossing 2007:116):

\[
\alpha = 8.686f^2 \left\{ 1.84 \times 10^{-11} \left( \frac{p_a}{p_r} \right)^{-1} \left( \frac{T}{T_r} \right)^{1/2} \right\} \\
+ \left[ \left( \frac{T}{T_r} \right)^{-5/2} \left( \frac{0.01278e^{-2.2391/T} f_{rO}}{f^2 + f_{rO}^2} + \frac{0.1068e^{-3.352/T} f_{rN}}{f^2 + f_{rN}^2} \right) \right]\}
\]

Where:
- \( \alpha \) = atmospheric absorption coefficient (in dB/m)
- \( e \) = Euler’s number
- \( f \) = frequency of the sound
- \( p_a \) = atmospheric pressure in kilopascals (see Eq. 6.2)
- \( p_r \) = reference atmospheric pressure at sea level = 101.325 kPa
- \( T \) = temperature (Kelvin)
- \( T_r \) = reference temperature = 293.15K (20ºC)
- \( f_{rO} \) = vibrational relaxation frequency for Oxygen (Hz, see Eq. 6.3)
- \( f_{rN} \) = vibrational relaxation frequency for Nitrogen (Hz, see Eq. 6.4)

(Eq. 6.1)

\[
P_a = 101.325 \left( 1 - 2.25577 \times 10^{-5} m_{\text{asl}} \right)^{5.25588}
\]

Where:
- \( P_a \) = atmospheric pressure (kPa)
- \( m_{\text{asl}} \) = altitude in meters above sea level

(Eq. 6.2)

\[
f_{rO} = \frac{p_a}{p_r} \left( 24 + \frac{(4.04 \times 10^4 h)(0.02 + h)}{0.391 + h} \right)
\]

Where:
- \( f_{rO} \) = vibrational relaxation frequency for Oxygen (Hz)
- \( P_a \) = atmospheric pressure in kilopascals (see Eq. 6.2)
- \( P_r \) = reference atmospheric pressure at sea level = 101.325 kPa
- \( h \) = percent relative humidity
\[ f_{rN} = \frac{p_a}{p_r} \left( \frac{T}{T_r} \right)^{-1/2} \times \left( 9 + 280 h e^{-4.17 \left[ \left( \frac{T}{T_r} \right)^{-1/3} - 1 \right]} \right) \]

Where:
- \( f_{rN} \) = vibrational relaxation frequency for Nirtogen (Hz)
- \( p_a \) = atmospheric pressure in kilopascals (see Eq. 6.2)
- \( p_r \) = reference atmospheric pressure at sea level = 101.325 kPa
- \( T \) = temperature (Kelvin)
- \( T_r \) = reference temperature = 293.15K (20ºC)
- \( h \) = percent relative humidity

Unless the air is completely dry (0% humidity), sound absorption decreases as humidity increases (Lamancusa 2009:10.3).

Natural and anthropogenic barriers also affect the spread of sound. However, unlike the two forms of attenuation discussed above, when attenuation is the result of a partial barrier, sound is primarily diffracted around the barrier, though portions are also reflected back at the source or transmitted through the barrier. (Cowan 1994:11; Ver and Beranek 2006:126). This form of attenuation is calculated following Maekawa’s optical diffraction theory which makes use of the Fresnel number originally defined in the Kirchhoff-Fresnel theory of diffraction (Maekawa 1968; Rossing 2007:116). The Fresnel number is a dimensionless coefficient that quantifies “how far below the line of sight (relative to wavelength) the receiver lies” allowing for quantification of impacts that any particular barrier has upon a sound (Lamancusa 2009: 10.15).
The Fresnel number is dependent upon both the wavelength of sound being studied, as well as the specific geometry of the barrier in question and is expressed mathematically as follows:

\[ N = \pm \frac{2}{\lambda} (A + B - d) \]

Where:
- \( N \) = Fresnel Number
- \( \lambda \) = Wavelength of Sound
- \( A \) = Distance between the Source and the top of the Barrier
- \( B \) = Distance between the top of the Barrier and Receiver
- \( d \) = Straight line distance between Source and Receiver

(Eq. 7)

The Fresnel number is then used to calculate barrier attenuation using the formula:

\[ A_{\text{barrier}} = 20 \log \frac{\sqrt{2\pi N}}{\tanh \sqrt{2\pi N}} + 5 \text{ (dB)} \]

for \( N \geq -0.2 \)

otherwise \( A_{\text{barrier}} = 0 \)

Where:
- \( A_{\text{barrier}} \) = Barrier Attenuation
- \( N \) = Fresnel Number

(Eq. 8)

The spread of sound can also be impacted due to a variety of other causes, such as atmospheric turbulence and meteorological effects, ground effects, and vegetation attenuation. "Ground effect" refers to attenuation by soundwaves reflecting off of the ground surface, especially in the areas closest to the sound source and/or receiver in
areas where no barrier is present to block the receiver. Interference caused by these reflected waves is greatest in the areas within 30 times the source height (source region) and 30 times the receiver height (receiver region). The middle region, which exists if the sum of the source and receiver regions is less than the total distance between the source and receiver, experiences less interference due to ground impedance (ISO 1996:9-12; Lamancusa 2009:10.9).

The presence of vegetation contributes to ground effects (e.g., porosity of the humus horizon), and provides additional attenuation due to the branches and trunks of trees scattering sound, as well as friction losses when sound travels through foliage (ISO 1996:20; Lamancusa 2009:10.14; Rossing 2007:129). There are a variety of methods of calculating vegetation attenuation, ranging from the use of tables and charts to look up attenuation values (e.g., Beranek 1988:182-3; ISO 1996:19; Lamancusa 2009:10.14; Rossing 2007:129); to formulae derived from fitted curves, which are more suitable for computer modeling (e.g., Aylor 1972; Beranek 1988:184; Lamancusa 2009:10.14).

Atmospheric turbulence, or fluctuations of temperature and wind speeds, can result in variabilities of amplitude and phase of sound waves, impacting Sound Pressure Levels. For example, as temperature decreases sound refracts upward. This is typical of daytime conditions (i.e., negative temperature gradient). At night, when the ground absorbs heat, soundwaves refracting towards the lower temperature may travel further along the surface. Wind also causes increases or decreases in sound speed, depending on whether the receiver is downwind or upwind from the source respectively. Because sound refracts towards the lower speed, soundwaves can bend upward creating an
upwind shadow zone. In a windy location that is also experiencing temperature gradients, wind effects will take precedence (Lamancusa 2009:10.10; Rossing 2007:131).

While many of these additional environmental impacts are possible to quantify when modeling the contemporary spread of sound, the ability to include these quantifications in archaeoacoustics varies based on the availability of pre/historical data including climatological and botanical data for the culture and period being explored. When this data is available and it is possible to do so, it should be included to improve the accuracy of the modeling scenario. However, many of these additional effects which may impact the spread of sound are termed “miscellaneous” and are not included in the general method of calculating sound attenuation presented in international standards (see ISO 1996).

**Acoustic Standards Applicable to the Archaeology of Sound**

Acoustic science provides a number of highly accredited standards for defining and calculating acoustic terminology and values, such as those written by the American National Standards Institute (ANSI) and the International Organization for Standardization (ISO). Written by committees of acoustical professionals, extensively peer-reviewed, and approved by “a consensus of experts,” these standards have been used to set legal requirements for acoustic measurements in modern environmental noise assessments (Cowan 1994:68). As illustrated by their incorporation in the previous section, contemporary archaeoacoustic study should utilize acoustical standards for purposes of
scientific accuracy. This section briefly reviews a number of these standards and describes their potential application to archaeoacoustics.

The first group of standards (ISO 9613-1, ISO 9613-2, ANSI S1.26) contain important formulae used in calculating the “predicted” spread of sound. Modeling tools, such as the Soundshed Analysis Tool, incorporate these formulae to recreate the behavior of sound in a free field. Sound analysis following these standards can be done 100% remotely.

ISO 9613-1 (1993) - As indicated in the section above, this standard provides the formulae for atmospheric absorption of sounds produced outdoors. Lookup tables containing atmospheric absorption coefficients are also presented, as is an example of A-weighted SPL attenuation calculations (see Annex E). This standard should be used in concert with part two to determine the attenuation of sound in a free field.

ISO 9613-2 (1996) - Part two of this standard describes attenuation of outdoor sound produced by a point source due to “physical mechanisms,” including: geometrical divergence (e.g., spreading losses); ground effect; reflection from surfaces; and screening by obstacles. It also describes the incorporation of atmospheric absorption as calculated following Part 1 of this standard. Annex A, provided for informative purposes, discusses miscellaneous forms of attenuation including losses due to foliage, and propagation through industrial sites or the built environment. This standard should be used in conjunction with part one to determine the attenuation of sound in a free field, or attenuation occurring within the near field if applying information contained in Annex A.
ANSI S1.26 (1995) - As stated in the forward of this standard, it is the “counterpart” of ISO 9613-1, and the “technical requirements... are identical.” The ANSI version provides an additional annex for calculating atmospheric attenuation under highly absorptive conditions, or at a location far from the sound source. This standard can be used interchangeably with ISO 9613-1 for calculating atmospheric absorption.

The second group of standards (ANSI S12.9-1, ISO 1996-1, ISO 1996-2, ANSI S12.18, ISO 3382-1, ISO 3382-2, ISO 3382-3) describes how sound measurements should be made within the environment or enclosed space, as appropriate. For archaeoacoustic applications these standards are best applied during fieldwork though they may also involve some general information or post-processing mathematical corrections.

ANSI S12.9-1 (1988) – This standard provides written and mathematical definitions for terms such as “Sound Pressure Level,” “Time-Average Sound Pressure,” “Sound Exposure,” and others. Of particular use to archaeologists is a section describing measurement locations and conditions for instrumentation, as well as notes about these conditions which should be recorded such as atmospheric conditions or the presence of reflective surfaces. This standard is brief but provides an excellent introduction to preparing for archaeoacoustical fieldwork.

ISO 1996-1 (2018) – This standard is the international counterpart of ANSI S12.9. Notably, in modern acoustical science American and European noise analysis often employ different time-weighted and frequency-weighted SPL measurements. The type of
measurement being reported is always included in modern analyses, therefore, if archaeologists use modern SPL data as a correlate for past acoustic conditions, the weighting method should be reported along with the SPL. For example a value of 55 dB $L_{den}$ specifies a day-evening-night sound level. Written and mathematical definitions for these terms are provided in this standard.

ISO 1996-2 (2007) – Part two of this standard describes how to measure and assess sound in the environment either by taking field measurements and employing corrections, or by “desktop” analysis. It includes suggestions for placement of microphones both indoors and outdoors and provides a list of information that should be recorded and reported. Interestingly, it notes that “there are no internationally recognized complete calculations methods (ISO 2007:14)” and points to the use of national standards when appropriate. Archaeologists should, therefore, make use of ANSI S12.18 described immediately below, or consult Annex E within ISO 1996-2 for a list of other source-specific calculation methods as appropriate for their study area.

ANSI S12.18 (1994) – This standard describes the method for measuring sound pressure levels outdoors created by a specific source or set of sources with corrections made for ground and atmospheric effects. The contents are the field methodology components of the calculations and formulae presented in ISO 9613-1, ISO 9613-2, and ANSI S1.26 described in “group one” above. In addition to acoustic measurements, this

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18 For example, the World Health Organization’s Environmental Noise Guidelines for the European Region (WHO 2018) uses the $L_{den}$ weighting system. A definition of $L_{den}$ is provided in ISO 1996-1:2018.
standard describes other data about the sound source and surrounding environmental and atmospheric conditions which should be recorded as part of the analysis, and provides two step-by-step methodologies: general, and precision. Instrumentation and reporting specifications are also provided. Archaeologists should apply the contents of this standard when field verifying the results of desktop sound modeling produced using the methods described in the “group one” standards. This standard may also be used independently of desktop noise modeling when designing archaeoacoustical fieldwork and data collection protocols for investigating sound produced by a specific source (e.g., an instrument which will be played on-site). Archaeologists doing fieldwork in archaeoacoustics should at a minimum familiarize themselves with the contents of this standard to ensure sound practices.

**ISO 3382-1 (2009)** – This standard describes how to evaluate acoustics within a “performance space.” In modern acoustical science, a performance space denotes an enclosed room, such as an auditorium, although archaeologists may apply the techniques described herein to caves or other enclosed areas. Impulse response methodology, including testing, measurement, and recording procedures are defined, as is reverberation time as an element of analysis. Many of the case studies previously discussed in Chapter 2 of this dissertation make use of these concepts (Díaz-Andreu et al. 2014, 2017, 2019; Díaz-Andreu and García Benito 2015; Díaz-Andreu and Mattioli

19 Archaeologists should take special care in their definitions when describing outdoor areas as “performance spaces.” While the term may be accurate for archaeological purposes, “performance space” is used to specify *enclosures* in acoustical science.
ISO 3382-2 (2008) – Part two of this standard applies the same acoustical evaluations using impulse response and reverberation time to “ordinary rooms” such as those in houses, offices, stairways, workshops, and enclosed sports halls. Three methodologies with increasing levels of precision are presented. In effect, archaeologists studying a variety of quotidian spaces may find these methods more suitable for investigating the acoustics of an enclosed space than those described in part one.

ISO 3382-3 (2012) – Briefly, part three of this standard applies the same evaluation methods to modern “open floor plan” offices. Although archaeological correlates may exist (a case could potentially be made for longhouses or other partitioned enclosures), it is likely that many enclosed spaces of the past more closely resemble those described in parts one and two.

The third group of standards (IEC 60268-16, ANSI S3.5, ISO TR 4870) applies specifically to studies on the intelligibility of speech at a given location through application of various indices. Some existing methods of rating speech intelligibility are detailed, and guidance is providing on creating site specific speech intelligibility tests using a standardized format.

IEC 60268-16 (2003) – Four methods for determining speech intelligibility are described in this standard. Two of these, the “Speech Transmission Index” and “Room Acoustics Speech Transmission Index” are of interest to archaeologists as they evaluate
speech transmission unaided by modern communications devices. Weighting factors for male and female speakers are also provided.

ANSI S3.5 (1997) – This standard provides methods and formulae for modeling the Speech Intelligibility Index (SII). Lookup tables provide band importance coefficients as well as standard speech spectrum levels. Use of this standard allows for speech intelligibility to be determined mathematically without creating and performing a speech intelligibility test.

ISO TR 4870 (1991) – This technical report provides guidance on creating robust speech intelligibility tests which result in meaningful measurements. The speech material utilized and the total quantity of possible speech material which could be utilized in the test are the two dominant factors to consider when developing a standardized method. Often these tests use Logatoms, which can be either monosyllabic or polysyllabic, and are based on the sounds used within the speaker's and listener's common language but are not “words” (i.e., do not possess meaning) in that language. This guidance is equally useful to acoustical scientists or archaeologists investigating speech transmission from one point to another on-site.

While the above standards should be used as a starting point for archaeoacoustical inquiry, other standards may contain some additional information which can be creatively applied. For example, part five of ANSI S12.9-5 (1998) describes sound levels within the “noise environment” and land-use compatibility. The standard is designed for modern planning purposes where predicted noise levels can be compared
with compatibility measurements provided in Figure A.1 for both indoor and outdoor noise sources. An archaeological application of this data could include use of the average SPLs provided in Figure A.1 as an indicator for past sound. For example, livestock farming and ranching ranges from 45-65 dB, while cemeteries and residential areas with outdoor use are both expected to be quieter by comparison.

**Acoustic Science on “Soundscapes”**

As illustrated by the example of “performance space” given in the previous section, archaeologists studying sound should pay particular attention to the potential for misuse of defined terms from acoustical science. Interdisciplinary study has recently led the ISO to release guidance on terms which are often appropriated by the humanities. ISO 12913-1 (2014) begins by stating “Soundscape studies have a rich tradition. Because the field has evolved differently around the world, as well as across disciplines, there is a diversity of opinions about its definition and aims. Consequently, the use of the term ‘soundscape’ has become idiosyncratic and ambiguous (ISO 2014:v).” Compare, for example, the definition of soundscape provided by Scullin and Boyd (2014) with two definitions from ISO 12913-1:

**Soundscape** – “…a 'soundscape' includes all sounds present in any given environment and how these sounds interact within that environment (Scullin and Boyd 2014:363).”

**Acoustic Environment** – “Sound at the receiver from all sound sources as modified by the environment (ISO 2014:1).”
**Soundscape** – “Acoustic environment as perceived or experienced and/or understood by a person or people, in context (ISO 2014:1).”

As illustrated above, the definition of “soundscape” employed in archaeoacoustics contemporaneously with the publication of the ISO standard differs from the way the terms are defined in acoustical science. In this case, while Scullin and Boyd were primarily describing the acoustic environment as noted by the similarities in the definitions above, their study did go on to consider the differences between modern perception of the acoustic environment with potential perceptual differences in the past (i.e., perceiving the past as an “out of tune” soundscape) (Scullin and Boyd 2014:376-7).

According to acoustic science, perception of the acoustic environment involves: (1) the interplay of sound sources and acoustic environment; (2) the influence of context on: auditory sensation; “attitude”, or the interpretation of auditory sensation; and responses to the acoustic environment; and (3) the resulting outcomes of this perceptual system (see ISO 2014:2 Figure 1). While sound sources and the acoustic environment constitute quantifiable acoustic data, the remaining elements of the perceptual system that inform “soundscape” are influenced by a combination of psychoacoustics and anthropological data. Anthropological theory and a long tradition of archaeoacoustic methods already fit neatly into this acoustic science schema of perception, all that

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20 While the sound source may be derived from archaeological data (e.g., an instrument recovered from a site location) the acoustic science definition of the discrete term “sound source” separates the object producing the sound from the “context” while acknowledging their interrelationship.
remains is for contemporary archaeoacoustic study to adopt shared terminology with acoustic science for improved interdisciplinary understanding.

**Psychoacoustics: The Perception of Sound**

At the beginning of this chapter, sound was defined as “…a disturbance propagated through an elastic material [that] causes an alteration in pressure or a displacement of the particles of the material which can be detected by a person or by an instrument” (Beranek and Mellow 2012:5, emphasis added). A unique aspect of this definition of sound is its reliance on a receptor; without someone or something to experience the sound, it is as if the sound does not exist.

The field of psychoacoustics, which examines the relationship between sounds (i.e., physical stimuli) and hearing (the sensations and perceptions experienced by the listener) allows us to approach the interaction between human physiology, sound physics, and perception (Plack 2005:3-4). Physiologically, the ear is composed of three sections (outer, middle, and inner ear) which contribute to the hearing process. In the outer ear the pinna funnels sound into the ear canal providing a gradual cross sectional change to minimize impedance, like the bell of a horn. This leads soundwaves to the tympanic membrane, or eardrum, causing it to vibrate. The middle ear is bounded by the eardrum, cochlea, Eustachian tube\(^{21}\), and bone. It contains three ossicles (the malleus, incus, and

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\(^{21}\) The Eustachian tube connects the air cavity within the middle ear to the back of the throat, which is why air pressure within the middle ear can be regulated through yawning (Cowan 1994:24).
stapes) held by ligaments within an air cavity that amplify the acoustic signal received at the eardrum 20 times while carrying it to the inner ear (Cowan 1994:22-3; see Lamancusa 2001:2.3-2.4 for a detailed discussion). Amplification is vital because the inner ear is filled with fluid and energy loss occurs when sound passes from air to fluid. After sound reaches the oval window at the middle to inner ear boundary, the energy causes the fluid within the cochlea to vibrate. The spiral shaped cochlea is filled with small hair-like nerve cells which send electrical signals to the auditory nerve and brain (Cowan 1994:24-5).

People react to the physical stimulus of sound through perception, so a sensation exists for each physical property of a sound wave. For example, people's perception of sound includes both its loudness and pitch. These subjective responses are reactions to the sound's amplitude and dominant frequency respectively (Beranek 1993; Cowan 1994; Cross and Watson 2006:109–10). Because “loudness” refers to a subjective measurement, the human experience of “loudness” is generally assessed using the physical magnitude of intensity or Sound Pressure Levels (SPL), as defined mathematically above. The SPL of human hearing ranges from 0 dB to 120 dB, where sounds can cause pain to the listener (Cowan 1994:36; Plack 2005:115-6). Recalling from above that decibels represent a logarithmic ratio, this is because the threshold of pain is roughly one million million (i.e., $10^{12}$) times the intensity of sounds at the threshold of

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22 As discussed in a previous section, humans are generally more sensitive to certain sound frequencies, therefore, the A-weighted decibel scale is typically used to reproduce the frequency sensitivity of the human hearing range. This scale, referred to as dBA, originates at 0 dBA where sounds are first heard, and ranges to 120 dBA, the “threshold of pain” (Cowan 1994:36).
hearing (Plack 2005:14). An increase in sound intensity by a factor of 10 (e.g., an increase of 10 dB) is, therefore, perceived as a doubling in loudness, while SPL changes of approximately 3 dB would be narrowly perceptible (Cowan 1994:34; Plack 2005:119).

The term “noise” is simply defined as “unwanted sound” and, therefore, has a perceptual component as part of the greater soundscape (Cowan 1994:274; Lamancusa 2000; Scullin and Boyd 2014). As observed by Beranek, people’s reaction to various noises within the same study and under the same conditions can change as the listener’s own attitudes change (Beranek 1993:389). This same type of subjectivity within a group of listeners would constitute cultural and individual perceptions of specific noises, each with its own meaning and purpose.

Humans experience changes in the fundamental frequency of a sound as a change in pitch. ANSI S3.20 defines Pitch as “that attribute of auditory sensation in terms of which sounds may be ordered on a scale extending from low to high. Pitch depends primarily on the frequency of the sound stimulus, but it also depends upon the sound pressure and waveform of the stimulus (ANSI 1976:38).” Although scholarly definitions of pitch differ, for example Plack’s definition of pitch as “that aspect of auditory sensation whose variation is associated with musical melodies (2005:133, emphasis in original),” reliance on the terms “musical” and “melodies” may in fact be difficult when studying archaeoaoustics, as for most of pre-history contextual definitions of these terms are lost. Nonetheless, archaeologists studying musical instruments of the past would recognize the sensation of pitch when the instrument is played.
Pitch is achieved when a waveform repeats at the same rate, called the “fundamental frequency” of the tone. Complex tones are made up of multiple pure tones that “are always integer multiples of the inverse of the duration of the waveform that needs to be produced (Plack 2005:18).” Therefore, a waveform lasting 100ms would consist of whole number multiples of a fundamental frequency of 10 Hz, also known as the “first harmonic” (20 Hz would represent the second harmonic, and so forth). The range of frequencies that can produce the sensation of pitch ranges from approximately 30 to 5000 Hz (Plack 2005:18-22, 133-5).

Another very important aspect of psychoacoustics is spatial hearing. Our auditory systems localize sounds to determine where a sound source is located; to direct the attention of our other senses; to determine sequences of sounds; and to focus in on a specific sound when presented with a cacophony of competing sound sources. While our visual abilities may be more sensitive than our auditory system, viewing is strictly an active experience (Plack 2005:173). For a site, landmark, or object to be seen an observer must actively engage in looking by directing their eyes towards the object of their perception. This is true regardless of whether the individual is intentionally looking for that particular site or if it is observed incidentally while looking at something else. By contrast, culturally produced sound requires both an active sound source and at least one person to perceive it.

However, even when multiple individuals hear a sound, they may not share the intention of participating in the same action. Those producing the sounds may not necessarily be producing them to be heard by others, such as sounds produced by
chopping wood or singing to one’s self, and auditory observation of culturally produced sounds at a site does not necessitate active listening. Some sounds, or noises are passively heard even by those engaged in activities other than listening. For example, the sound of the neighbors’ baby crying or dog barking may be heard by someone preparing food in a different residence, or a crowd in the plaza may be audible to a passerby on a parallel street, without those individuals listening with intent. Simply stated, while listening and viewing are active experiences, hearing can occur passively and without intentional participation by the perceiver.

Our binaural (i.e., using two ears) auditory systems locate a sound source by comparing differences in the sound level and arrival time between ears. The spatial resolution with which we locate a sound source varies depending on the source’s location relative to the listener. These locations are described using degrees of elevation (vertical tilt of the head) or azimuth (horizontal rotation), where front and center represents 0º, directly left is the 90º azimuth, and directly overhead is the 90º elevation (Moore 2003:233-5; Plack 2005:174-6). Unless a sound is located directly in front or behind a listener (0º or 180º azimuth), the head causes diffraction of sound waves, as would any partial barrier, resulting in different arrival times between ears called “interaural time differences (or ITDs)” (Plack 2005:176). Humans can detect a stable ITD of 10 microseconds, which translates to a sound source position change of about 1º azimuth relative to the head. That said, if the sound source is moving back and forth rapidly, creating a sinusoidal variation in ITD, our ability to accurately locate the source diminishes significantly (Moore 2003:235-8; Plack 2005:177).
Interaural level difference (ILD) works in a similar way to ITD in our binaural systems, whereby the sound intensity at the ear located further from the sound source is lower than that received at the ear directed towards the source. Again, unless a sound is located in the median plane at 0º or 180º azimuth, the head functions as a barrier, resulting in diffraction and sound shadowing. According to Plack, “the smallest detectable interaural level difference is about 1-2 dB” (2005:178-9, emphasis in original). Information gained through ILD, which works best for high frequency tones, and ITD, which works best for low frequency tones, is used in concert to improve locational acuity. To resolve the location of a source located in the median plane, one simply needs to turn their head to experience ILD and ITD (Moore 2003:235-8; Plack 2005:179-85)\(^\text{23}\).

Archaeoacoustic studies further differentiate between the concepts of audibility – the perception of sound – and speech intelligibility. SPL is the property of sound that is most indicative of audibility. The distinction between passive and active audibility as mentioned above is just one example of how the modeling of sound can enhance a modern reconstruction of the auditory experience. For example, increases in SPL above the background SPL but of less than 5 dB can be perceived if actively listened for; whereas a 5dB or greater increase in sound pressure level is clearly noticeable. This

\(^{23}\) Note that in particularly resonant small rooms or caves, sound reflections may cause conflicting ILD and ITD information, which may result in the listener to believing the sound source is located at the position where the reflection occurred. For a detailed discussion of this, refer to Plack (2005:187-90) or Moore (2003:253-6). For an archaeoacoustic application of these principles, see Kolar (2013, 2017).
noticeable change constitutes the “passive” audibility threshold at which a person would perceive a sound even while engaged in other activities (Cowan 1994:34-36).

Speech intelligibility differs from audibility in that the listener must both hear and understand a verbally encoded message coming from the speaker. Psychoacoustic study has shown that human speech signals contain several redundancies to help ensure the message gets across. Speech can withstand a large amount of spectral smearing and filtering if the temporal components of speech remain unaltered, or, in cases of temporal fluctuation, speech can be understood if spectral signals are maintained (Plack 2005:224-6). In addition, when the speaker and listener share the same native language, the brain can amalgamate the available information to improve intelligibility and even provide the impression of uninterrupted speech. Studies have shown that when speech signals are degraded the brain perceptually restores the missing information by drawing context from subsequent words. Furthermore, listeners have been shown to identify about 80% of words correctly, even when presented with as little as 50% of the message (Plack 2005:224-6, 231-2).

As discussed previously, acoustical science provides us with existing standards for calculating the Speech Intelligibility Index (SII) and the Speech Transmission Index (STI), however, STI is typically calculated for enclosed spaces with reflective surfaces. Therefore, proxy measurements such as the signal-to-noise-ratio can be substituted for measuring SII when applied to landscape archaeological studies that calculate outdoor sound propagation and free-field acoustics (e.g., Jovičić 1991; Larm and Hongisto 2006; Lazarus 1986). All archaeoacoustical studies are influenced by psychoacoustics, a mix
of physical behaviors of sound (e.g., spreading, transmission losses, etc.) and human perception; therefore, these aspects will be discussed further in relation to specific case studies in Chapters 7-9.

Archaeoacoustics and Cultural Anthropology of Sound

Thus far, this chapter has demonstrated the invaluable contributions of acoustic science, sound physics, psychoacoustics, and human psychology to the field of archaeoacoustics. However, as Watson reminds us, “principles of acoustic physics are largely built upon nineteenth- and twentieth-century concepts of sound waves, and the mathematical principles that underlie them (e.g., Rayleigh 1896), and would be largely meaningless to people living outside the Western and modernist paradigm upon which science is itself founded (2006:19).” As Krause reflected upon his own ecological training:

“I was formally educated in the classical manner of scientific and cultural deconstruction. This kind of reductionist fragmentation taught me to segment the components of the natural world into its various parts. I learned how to distinguish one species from another, and to pay particular attention to the sounds of single members of individual species. Yet to truly understand the relationships between components, I recognized early on that without a more inclusive perspective, a vital dimension of the picture was missing; I realized that the collective voicings of entire habitats contained a far more complete package of information (2016:25).”
Taking a step back from the modernist western perspective, archaeoacoustics may also benefit from a holistic approach to the sound environment, and a cross cultural exploration of sensory engagement.

In describing and immersing oneself in the ecology of the sound environment we may speak of three categories of sounds: geophonies, biophonies, and anthropophonies. Krause describes these as follows:

Geophony: “the original source of sound on earth, made up of non-biological natural sounds such as the effect of water in marine environments, wind in the trees, thunder, rain, earthquakes, avalanches; the first of three elements in the soundscape24 (2016:195);”

Biophony: “the collective sound that whole groups of living organisms produce in a given ecosystem; the second of three components of the soundscape (2016:194);”

Anthropophony: “the final component of the soundscape that includes two subclasses of human-generated sound. The first of these subclasses is controlled sound, including music, theater, and language. The second of these subclasses is incoherent or chaotic sound, often referred to as noise (2016:193).”

24 Note that in his book, Krause’s use of the term "soundscape" is generally more in keeping with the ISO definition of the term "sound environment," however, in many cases he uses the term interchangeably to reflect upon perceptions/context of the sound environment (i.e., consistent with the ISO definition of "soundscape") as well.
These categories have already been adopted by archaeologists including Mills, Díaz-Andreu, and Mattioli, who all expand upon definitions of anthropophony to include incidental sound, sounds produced by human created technology (e.g., traffic, the “twang” of a bow string when an arrow is fired), or sounds produced due to human action upon unmodified natural surfaces or waterbodies (e.g., lithophones, rock gongs) (Díaz-Andreu and Mattioli 2016:1050; Mills 2014:96). As Mills relates: “Considering and adopting different ways of categorising [sic] and organizing [sic] sounds allows a flexibility in approach that can be tailored to the specific requirements of a given research project as determined by the research questions posed, the available evidence and logistical constraints (2014:96).” Consideration of sounds from a variety of categories such as these create a more inclusive study base for modern researchers, and prove useful when describing spatiotemporal and other relationships between sounds.

We need only to return to the previously discussed works of Watson (2006) and Waller (2002) to review some non-western treatment of acoustic phenomena; or that of other researchers in archaeoacoustics today. Watson relates an example drawn from Papau New Guinea’s Ilahita Arapesh. There, players of particular instruments (hourglass drums into which bamboo pipes were played) “were said to have assumed god-like powers,” speaking with the voices of spirits (Watson 2006:12). In this case, the intent was not to create music, nor was a primary connection drawn between a person and the playing of an instrument – the purpose was to at least temporarily allow listeners to hear the voices of gods (Watson 2006:12-3). Waller details a series of legends surrounding echoes, spanning North, South, and Central America; Asia; Europe; and the South
Pacific. In some cases echoes were personified; in others, as is the case with India’s Korku tribe, echoes are still important selection criteria for placement of petroglyphs (Waller 2002:12).

Rainio et al. include a discussion of early twentieth-century ethnography in their treatment of Finnish rock art sites. These records describe how a particular cliff called Taatsinkirkko (“Taatsi church”) was utilized by the Sámi people as a place of ritual sacrifice of fish and reindeer called a sieidi. The cliff was known and valued for its acoustics: “Water runs and drops there and echoes, as if someone was preaching. It is like a room […] [The Sámi sang their sieidi-prayers there because the cliff resounded (Rainio et al. 2018:456-7).” The authors further explain that the translated term “sieidi-prayer” refers to magical singing called joik in which the Sámi shaman would sing, occasionally accompanied by playing a drum, until they entered a trance. In Sámi culture, joik singing was said to be “given to mankind by the people of the underworld (Rainio et al. 2018:456-8).”

Like Taatsinkirkko many place names retain ethnohistorical evidence as to the importance of acoustics at a site. The Navajo name Tse’Biinaholts’a Yalti or “concavity in the rock that speaks” belongs to an amphitheater feature in Chaco Canyon, New Mexico which responds to acoustic input through amplification, standing waves, reverberation, and other effects (Loose 2008:31-9). A prolific rock art location, Ndedema Gorge (or “Didima Gorge”) in South Africa takes its name from a language belonging to the Nguni group (e.g., Zulu or Xhosa) and means “place of reverberation” – a reference to echoing
effects during thunderstorms. This is a possible adaptation of an earlier /Xam term, *lgum*, “to road, bellow, [or] call (Mazel 2011:291-2).”

In attempting to overcome western biases I advise a reading of Howes (2008), who’s suggested employment of a tripartite anthropology of the senses was presented in Chapter 3. For example “…forests lead people astray or hide cattle, sacred places punish transgressors who violate taboos…” much as personified echoes possess agency in Waller’s accounts (Valk & Sävborg 2018:8; Waller 2002). In cases where a representation of the emic perspective may be otherwise unattainable, a reading of Hamilakis’ Eleven Theses on the Archaeology of the Senses may provide a helpful framework (2013a). In particular: thesis three, which addresses synesthesia rather than modern/western sensory modalities; and thesis four, which addresses the use of the “individual” perceiver as a unit of analysis (Hamilakis 2013a:410-2).25 In-depth discussions of sensory engagement and, when possible, a view of the emic perspective will be provided in each of the three case studies appearing in Chapters Seven through Nine.

Discussion

Cross and Watson (2006) provide an excellent review, situating both acoustic science and psychoacoustics within an archaeological framework. Even unintentionally created acoustic effects (e.g., within buildings or semi-enclosed features) would have

25 Although theses eight and ten do not belong in the current discussion, eight is notably quite valuable for research in performance theory/political theater, and ten for phenomenological work as described previously in Chapter 3.
been noticeable in prehistory, and as described above each aural perception corresponds to physical phenomenon that enable study. For example, Sound Pressure Levels vary across a site, and measurements should, therefore, be taken at different positions. These measurements may then be used to indicate the best locations for public events featuring sound, including both the placement of the speaker (or other sound source) and the participants or audience (Cross and Watson 2006:107-110). Objective Clarity, a “measure of the ratio of direct sound to indirect sounds in an enclosed space” also varies across a site and can be determined through measurements of reverberation time and early decay time (Cross and Watson 2006:109). These measurements can be used to describe whether “heightened speech” such as singing was intelligible or whether sounds blurred together creating illusory effects (Cross and Watson 2006:110-1).

The interplay of science, sensation, psychology, and culture defines archaeoacoustics. Methods partially derived from acoustical science applied in tandem with theories of perception provide archaeology with new avenues for exploring the evidence for and potential utilization of sounds of the past. Acoustic reconstruction reaches towards a holistic sensory perspective of a site and the experiences of those who were present to hear. In the chapters that follow, I will apply these principles, describing first the methodology (chapters five and six) and its application to case studies (chapters seven through nine).
Chapter 5. Tool Development and Validation

The purpose of this study is to establish a methodology for modeling and exploring the estimated spread of sound throughout anthropogenic landscapes. Reaching this goal requires the development of a tool capable of reliably modeling the spread of sound, pairing the tools with one or more theoretical milieu, and providing case studies demonstrating the application of this tool in a variety of sociotemporal, cultural, and environmental settings. The Archaeoacoustics Toolbox represents a methodological advance in the study of the experience of past populations, and provides a contextualizing framework by which researchers can approach auditory hypotheses, performance spaces, embodied experience, and other foci of inquiry.

While the ISO definition of the term “Soundshed” was provided in the previous chapter, use of the term “Soundshed” as appearing in the title of the Soundshed Analysis tool is meant to mimic the name of the ready-made “Viewshed” analysis tool available for use in Environmental Systems Research Institute’s (ESRI) ArcGIS. A growing body of literature interpreting visibility and intervisibility in archaeological contexts has made use of the push-button functionality of the “Viewshed” tool, which produces a raster dataset of locations that are visible “1” or not visible “0” from an observation point. Variations on this tool for ArcGIS 10.3 include Viewshed 2, Visibility, and Observer Points which collectively add the ability to identify the visibility of observers. Although sound modeling is not currently available from ESRI in an ArcGIS tool, ESRI allows users to design their own add-on tools, toolboxes, and modeling workflows using options such as ESRI's model builder, or via the programming language Python.
Model Builder is a proprietary ESRI platform that allows users to create workflows using sequences of existing ArcGIS tools, as an alternative to writing fully original scripts. Segments of user input code can be inserted into model builder as needed to perform the calculations or operations lacking predefined ArcGIS tool syntaxes. Python is an open source programming language that integrates with ESRI software, but is not an ESRI product. Python includes a sizeable standard function library, as well as specific modules such that provide access to specialized coding functions. For example, the “math” module provides access to mathematical functions such as logarithms, trigonometry, and mathematical constants, and the “arcpy” module provides code for ESRI geoprocessing functions and tools (Python Software Foundation 2001).

Although both modeling options would be viable, use of Model Builder was rejected as an option for designing a sound model for several reasons:

1. the proportion of coding needs for user defined acoustical functions to complete the sound physics calculations was significant enough that substantial coding would have been required to supplement model builder processes;

2. creating an entirely scripted tool allowed the syntax to be modified within a single Python IDE (integrated development environment) rather than a combination of Python and Model Builder interfaces;

3. A similar open-source Python script capable of modeling the spread of sound, “SPreAD-GIS” (Reed et al. 2009, 2010) was already available and
could be used as a starting point for modification to archaeological sound modeling purposes.

Ultimately, use of Python allowed for the creation of a versatile and adaptable tool as described in Phase 2, the code for which could be modified further for use in diverse study areas, or to address various research hypotheses.

After a team of researchers from The Wilderness Society’s Center for Landscape Analysis in San Francisco compared available acoustical modeling solutions, “SPreAD-GIS” was created by migrating an older modeling system “SPreAD” to GIS using model builder (Reed et al. 2009:6-7). SPreAD, or “the System for the Prediction of Acoustic Detectability,” was developed by the US Forest Service in the 1980’s to evaluate the impact of noise on recreationalists visiting national forests and parks (Harrison et al. 1980:ii). SPreAD’s noise calculations were performed by hand using worksheets and lookup tables (Keyel et al. 2017; Reed et al. 2009:7) based on established acoustical formulae but predating international standardization – most notably the international standard on outdoor sound propagation ISO 9613-1 (1993) and ISO 9613-2 (1996). The authors of SPreAD-GIS made an effort to incorporate some formulae from these standards within portions of their code during the conversion process (see code documentation available in Reed et al. 2009, 2010).

As part of this research, portions of the functionality within SPreAD-GIS have been further adapted and modified to create the Soundshed Analysis Tool and the Archaeoacoustic Toolbox series, beginning with a change in geoprocessing syntax to migrate the tool from an ArcGIS 9.3 environment to an ArcGIS 10.3 environment (or later
Adaptation also included: modifications that allow high-resolution modeling at a 1.0-1.5 meter resolution (i.e., LIDAR scale); modification and replacement of some of the sound physics formulae; and elimination of elements of SPreAD-GIS that can be too subjective for the modeling of past environments, such as upwind and downwind losses, which require a user to know the prevailing wind speed and direction, from the modeling parameters. A detailed comparison of the functionality of SPreAD-GIS and the Soundshed Analysis Tool can be found in Appendix A.

Most notably, the Soundshed Analysis Tool offers the user a choice of modeling resolution options, ranging from 1.0 m to 30.48 m (or 100 ft.). The modeling resolution is determined by the cell size of the elevation raster dataset forming the basis of analysis as the input and output rasters must align for the tool to work properly. Cells are square and cell size measures the horizontal dimension or width of the area covered on the ground when viewed from above. The smaller the cell size, the higher the raster resolution. Although LiDAR data is becoming more common, high resolution data isn’t available for all study areas. Therefore, this allows the user to select from a variety of elevation datasets, including LiDAR data (often 1.0 or 1.5 m resolution), Digital Elevation Models (DEM, often 10 m or 30.48 m resolution), or other elevation raster inputs such as Digital Surface Models or Digital Terrain Models. Regardless of the elevation raster resolution (cell size), the vertical units of the elevation raster must be Meters above sea level for use in soundshead analysis. Cell size differences can be seen in the code on lines

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26 Instructions on how to determine cell size, and other step-by-step directions for using the tool can be found in Appendix G.
The Soundshed Analysis Tool beta release version 0.9.3 script follows a seven step process:

1. **Input of parameters:** Eleven model parameters are input by the user consisting of a short model name and two categories of data (see Table 5.1). Environmental data for the study location includes: the air temperature (°F), and the percentage of relative humidity, both of which relate to the physical properties of the spread of sound in air as described in chapter 4; the ambient sound pressure level (SPL) of the study location measured in A-weighted decibels (dBA); an elevation raster dataset; and the resolution of the elevation raster dataset. The air temperature and the percentage of relative humidity may be used from historical records if such records exist, or gathered from modern data (either in the field or through modern data (either in the field or through

<table>
<thead>
<tr>
<th><strong>Cultural Variables</strong></th>
<th><strong>Environmental Variables</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td>Location of Sound Source</td>
<td>Percentage of Relative Humidity</td>
</tr>
<tr>
<td>Height of Sound Source (ft.)</td>
<td>Air Temperature (°F)</td>
</tr>
<tr>
<td>Sound Pressure Level of Source (dBA)</td>
<td>Ambient Sound Pressure Level (dBA)</td>
</tr>
<tr>
<td>Predominant Frequency of Source (Hz)</td>
<td>Elevation Data (mASL)</td>
</tr>
<tr>
<td>Measurement Distance from Source (ft.)</td>
<td>Elevation Raster Resolution (Cell Size)</td>
</tr>
</tbody>
</table>

**Table 5.1. Soundshed Analysis Tool v0.9.3 Input Variables**
meteorological literature searches) and corrected manually for climate changes over time. These meteorological variables should match the appropriate date and time of the modeling scenario, for example a cool dessert morning in winter or a humid tropical afternoon as appropriate for the sound or ritual being performed.

Cultural data describing the source of the sound includes: the study location saved as a point feature class; the height of the sound source in feet measured between ground surface and the primary location where sound is produced (e.g., the bell of a trumpet, the mouth of a speaker); the SPL of the source (dBA); the predominant frequency (Hz) of the sound source; and the distance in feet between the sound source and the location where the SPL of the source was measured. These variables may also be derived from literature reviews or from measurements taken while playing the instrument. If the instrument or sound producing device is a feature (e.g., rock gong) and measurements must be taken in the field, care should be taken to try to record measurements on a clear quiet day. Wind and other background noise can impact acoustical data.

All ten inputs and a model name are required to run the model (see Figure 5.1) and must be entered by the user before modeling can begin. Although the model name or nickname assigned by the user must be short (9 characters) to comply with ESRI’s naming conventions, automating this step of the process saves the user from manually renaming each file between modeling scenarios as further described in step 6. Once this step is completed, the user clicks “OK” to run the model and steps 2-6 proceed automatically with no additional user interaction.
Figure 5.1. Soundshed Analysis Tool 0.9.3 Graphical User Interface

2. Definition of the study area: The script “clips” out a portion of the elevation dataset within a distance of 3.2 kilometers (2.0 miles), reducing the elevation raster layer's spatial footprint and the amount of memory required for geoprocessing. This step results in increased geoprocessing speeds and improved toolbox stability. As described by Reed et al. (2009:14) this distance represents the area where sound could be audible, and sound is not likely to travel beyond 5.0 km. Clipping occurs between lines 66-81 of the python script, then this layer is set as the modeling
extent for the remainder of the script (lines 83-92). During this step the spatial footprint of the study area is also be used to create an “Ambient SPL” layer using the value input by the user during Step 1. The ambient SPL layer is created from lines 94-105.

3. **Calculating distance attenuation:** As a sound spreads away from its point of origin, its sound pressure level declines at a steady rate. According to the Inverse Square Law, sound pressure falls “as the reciprocal of the square of the distance from the source” or at an approximate rate of 6 dB as the distance from the source doubles (Cowan 1994:274). The Soundshed Analysis tool departs from the way this was modeled in SPReAD and SPReAD-GIS by adding the height of the sound source to the elevation dataset (one of the variables the user is required to define), the same way an “offset” function is used in viewshed analysis (see lines 121-142 of the script). Next the tool calculates the distance and direction to each point on the landscape from the sound source and divides the Euclidean distance by the measurement distance of the sound source and applies the distance attenuation formula (see Chapter 4, Eq.5). These steps occur between lines 144-161 with the distance attenuation formula appearing in lines 158-161. The interim values of the distance attenuation calculations are then subtracted from the “Sound Source SPL” raster dataset, and resulting values are saved in a distance attenuation layer available as on output at the end of the modeling process (see lines 163-175 of the script). In SPReAD-GIS, distance attenuation values are stored as temporary or intermediate data only. In both SPReAD-GIS and the Soundshed Analysis Tool,
the user has the option to locate and save other intermediate data created during this or other steps prior to their next use of the tool, however, any temporary layers that are not saved or exported before a subsequent run of the model will be overwritten. Temporary layers are saved in the SoundAnalysis > temp folder.

4. **Calculating atmospheric absorption loss**: Other than changes to the ArcPy (Python) syntax associated with the migration of the script to ArcGIS 10.3, this section of code (lines 177-248) retains the functionality appearing in SPreAD-GIS. The air temperature and relative humidity data input by the user in step one are utilized in determining the atmospheric absorption coefficient as described in ANSI S1.26 (1995). Atmospheric absorption loss is saved as a temporary layer only.

5. **Calculating viewshed, barrier attenuation, and topographic loss**: The presence of a barrier within the path of a sound wave does not necessitate that the sound will be inaudible on the other side. Barriers still allow for partial transmission of a sound through them, while diffracting some sound around the barrier and reflecting some sound back at its source (Ver and Beranek 2006:126). The Soundshed Analysis tool calculates barrier attenuation loss according to Maekawa’s optical diffraction theory (Maekawa 1968, see Chapter 4, Eq.8) using the Fresnel number (see Chapter 4, Eq.7), a “dimensionless quantity” (i.e., coefficient) that measures “how far below the line of sight (relative to wavelength) the receiver lies (Lamancusa 2009:10.15).” In effect, the results provide an estimation of how sound would be experienced at any location within the landscape. Like atmospheric absorption loss, barrier attenuation data is stored in a temporary layer. Barrier attenuation and
topographic loss are calculated between lines 250-403, and equations 7 and 8 referenced above can be found between lines 322-387 and 389-393 of the python script respectively. Viewshed is calculated using the sound source height as an offset (see lines 303-310 of the script) during this step.

6. Producing final outputs: Temporary datasets created in steps two through five above are used to derive cumulative effects (e.g., areas subject to both distance attenuation and barrier losses), and establish primary impact areas for each form of attenuation based on the soundflow path and associated topography (see lines 395-441 of the python script). Final soundshed model outputs include four layers:

   a. RA: This layer describes the SPL of the source as heard over the background SPL otherwise known as the “rise over ambient” dBA level (see lines 434-444, 446, 453-454 of the python script);

   b. PR: This layer depicts the general sound “propagation” pattern. Hypothetically, if the ambient SPL was 0 dBA this is the extent to which sound would spread in relation to the elevation dataset (see lines 408-432, 443-445, 450-451);

   c. SS: This layer, created in step 4, also depicts a hypothetical scenario, “spherical spreading.” This layer would represent distance attenuation if there were no barriers present to block the spread of sound (see lines 443-444, 447, 456-457 of the python script). The results are independent of the elevation dataset;

   d. VS: As described in step 7, the tool also created a “viewshed” for the sound
source, which is be saved as a final model output during this step (see lines 443-444, 448, 459-460). The viewshed relates to the elevation dataset and height of the sound source.

The sound propagation layer shows the path that sound would travel given a lack of background sounds, or an ambient SPL of 0 dBA. While the output data describing the rise over ambient sound pressure levels more accurately estimates how audible sounds would have been experienced for a specific scenario, retaining the general propagation pattern layer allows for at-a-glance understanding of where sound would be likely to spread at different ambient SPLs. Moreover, if all other input variables remained the same, the GIS raster calculator tool could be used to subtract a different ambient SPL value from the general propagation pattern layer to produce a new rise over ambient layer in a fraction of the time.

7. **Symbolizing the data**: Once modeling is complete, the user adds the data to an ArcGIS map, and defines its symbology. The native format of the output data is GIS “stretched” raster layers, which are typically symbolized using graduated colors, however, the raster data can also be displayed as “classified” data where colors are assigned to different numerical groupings or can easily be converted to vector data to be displayed using contour based isolines. A combination of these methods can also be used to call attention to various aspects of the spread of sound, such as thresholds of passive and active audibility and/or speech intelligibility.

In summary, the Soundshed Analysis Tool consists of a geometric-type model
which assumes sound travels through the air along straight-line paths. Directionality of the source and wave effects, such as reverberation, are not considered by the model. The tool uses formulae of outdoor sound propagation, calculating free-field sound attenuation following ISO 9613-2 (1996), atmospheric absorption loss following ANSI 1.26 (1995), topographic loss following ISO 9613-2 (1996), and barrier effects based on Maekawa’s optical diffraction theory (Lamancusa 2009; Maekawa 1968).

Prior to its application, use of the Soundshed Analysis Tool was tested in both a Windows 7, 32 bit Operating System (OS), and a Windows 10, 64 bit OS, and validated using modern environmental data. The principles of acoustics and formulae applied by the model are established scientific methods; the validation step confirmed that the GIS tool correctly performed these mathematical operations. Testing required existing literature on noise studies, with associated mapping, and available LiDAR data. Input data obtained from the literature were used to replicate sound modeling for these sites, and the Soundshed Analysis Tool’s results were compared with the findings of currently accepted noise analysis methodologies to provide a level of confidence in the model’s calculations.

LiDAR data with a 1.5 meter cell size was available for portions of Upstate New York. Information regarding noise studies was requested from the New York State Department of Environmental Conservation (DEC) and obtained pursuant to New York State’s Freedom of Information Law (Public Officers Law §87 et seq.). DEC provided application documentation, including noise analyses, for three Mined Land Reclamation Permits which are located within LiDAR coverage areas. Noise analysis maps from the
mining applications were georeferenced, and input values were determined from the
noise analysis narratives.

During the initial phase of model testing, two studies were used to evaluate the
functionality of distance attenuation calculations in the Soundshed Analysis tool: the
Brickyard Facility and the Weir Sand and Gravel Mine. The Brickyard Facility (DEC ID #4-
3842-00025) completed a noise analysis in 1995 as part of an Environmental Impact
Statement (EIS) (LA Group P.C. 1995; Long 1995). Two sound source locations were
modeled within the mine, and concentric circles representing distance attenuation were
provided on a sound assessment map. Modeling for the Brickyard site was completed
using the Soundshed Analysis tool input values shown in Table 5.2; corresponding results

**Table 5.2. Model Validation Input Variables**

<table>
<thead>
<tr>
<th>Model Inputs</th>
<th>Weir Mine</th>
<th>Brickyard Mine</th>
<th>West Wind Farms</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Model Time</strong></td>
<td>Humid July Day</td>
<td>Humid July Day</td>
<td>Humid July Day</td>
</tr>
<tr>
<td><strong>Sound Source</strong></td>
<td>Haul Road/ Mine Interior</td>
<td>Processing Equipment</td>
<td>Processing Equipment</td>
</tr>
<tr>
<td><strong>Sound Source Height (ft.)</strong></td>
<td>10</td>
<td>8</td>
<td>8</td>
</tr>
<tr>
<td><strong>Frequency (Hz)</strong></td>
<td>500</td>
<td>500</td>
<td>500</td>
</tr>
<tr>
<td><strong>Sound Level of Source (dBA)</strong></td>
<td>79.3</td>
<td>89.4</td>
<td>82.5</td>
</tr>
<tr>
<td><strong>Measurement Distance (ft.)</strong></td>
<td>75</td>
<td>50</td>
<td>50</td>
</tr>
<tr>
<td><strong>Temperature (f)</strong></td>
<td>72</td>
<td>72</td>
<td>72</td>
</tr>
<tr>
<td><strong>Relative Humidity (%)</strong></td>
<td>80</td>
<td>80</td>
<td>80</td>
</tr>
<tr>
<td><strong>Ambient dBA</strong></td>
<td>41.2</td>
<td>55</td>
<td>52</td>
</tr>
</tbody>
</table>

are displayed in Figure 5.2. The sound pressure level (dBA) measurements at 152 meter
(500 foot) intervals from the sound source locations (represented by colored rings)
substantially conform to those defined in the georeferenced sound assessment plan map (line drawing georeferenced prior to modeling), illustrating that distance attenuation calculated by our model conforms to previously established noise analysis methodology.

**Figure 5.2.** Brickyard Facility Distance Attenuation Results

The Weir Sand and Gravel Mine (DEC ID #4-3842-00089) was also the subject of an EIS in 2004 and additional noise analyses in 2005 (Griggs Lang Consulting Geologists, Inc. 2004; Milliman 2005). The projected increase in sound pressure levels at five receptor locations (residences) were each evaluated based on two sound scenarios. Modeling for
the Weir site was completed using the Soundsheed Analysis tool input values in Table 5.2, which were obtained from the mine’s Draft EIS (Griggs Lang Consulting Geologists, Inc. 2004:Section 7.3.1.2, Table 5). Again, the results of distance attenuation analysis substantially conformed with expected results, as shown in Table 5.3.

**Table 5.3.** Weir Sand and Gravel Mine Modeling Results Comparison

<table>
<thead>
<tr>
<th>Modeled Location</th>
<th>Comparison dBA</th>
<th>Receptor Number</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Haul Road</td>
<td>Receptor Number</td>
</tr>
<tr>
<td></td>
<td>Expected Sound Level</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>Model Results</td>
<td>45.9</td>
</tr>
<tr>
<td>Mine Interior</td>
<td>Expected Sound Level</td>
<td>49.3</td>
</tr>
<tr>
<td></td>
<td>Model Results</td>
<td>49.29</td>
</tr>
</tbody>
</table>

A third site, West Wind Farms, Inc. (DEC ID #4-3842-00110), was chosen to test the barrier attenuation aspect of the Soundsheed Analysis tool; this site underwent two noise analyses (Advanced Environmental Geology, LLC. 2014; Spectra Environmental Group, Inc. 2005a, 2005b; Sovas 2005a, 2005b, 2005c). The initial noise analysis published in 2005 determined that the existing topography and proposed berms would limit noise impacts to any neighboring residences. The constructed berms appear in the 2010 LiDAR data set (see Figure 3) approximately 75m east of the sound source location, allowing barrier attenuation to be modeled at the site. The modeling results corroborate the noise analysis provided by the applicant, indicating that artificial berms and natural ridges effectively diminished the spread of noise from the mine to neighboring residences.
By investigating these sites and comparing the Soundshed Analysis Tool’s estimated results with the results of currently accepted noise analysis methodology, this model could be validated. This provides a level of confidence in the Soundshed Analysis Tool’s calculations that would otherwise be absent.
Chapter 6. Toolbox Expansion – Variable Cover Tool

During the Soundshed Analysis Tool’s initial application to Chaco Canyon, New Mexico, a fairly homogeneous semi-arid desert landscape of scrub and grasses, some subjective calculations were removed from the script. The decision to remove wind effect and vegetation attenuation calculations was made based on two factors: lack of data, and lack of impacts when modeling the null scenario. For example, without reliable data on the prevailing wind speed and direction in prehistory, the user’s best option is to model a null scenario, in this case a calm day without wind. The same is true if the past vegetation cover and density are also unknown, or if the past landscape was only sparsely vegetated, such that the vegetation would not provide sound attenuation. In either case, subtracting a null attenuation value during the Sound Pressure Level (SPL) calculations results in the original SPL value. Simply put, retaining code to calculate these values would result in unnecessary geoprocessing time in cases where it is known that the null scenario will be modeled.

While the utilization of reconstructed vegetation models has been a source of debate (e.g., Cummings and Whittle 2003; Lyon et al. 1977; Peng et al. 2014), land cover and vegetation may have impacted the experience of past soundscapes. Recent reconstructions (e.g., Goodwin & Richards-Rissetto 2017; Guth 2009; Llobera 2007a) support the inclusion of vegetation in analyses to produce a full range of estimated soundsheds, particularly in study areas where past ecosystems and flora have persisted, essentially unchanged. For example, use of the Soundshed Analysis Tool in ecologically diverse areas can result in the production of audibility maps and models which do not
accurately reflect the vegetative and anthropogenic variation in some sonorous environments. To address this, a second tool was developed that calculates attenuation due to variable land-cover types, in addition barrier attenuation and atmospheric absorbance. The Soundsched Analysis - Variable Cover tool also includes the optional assignment of multiple ambient SPLs which can be based on cover type. For example, one ambient SPL in a dense semi-tropical forest, and another in garden orchards, or could be based on other user defined categories, such as ambient SPLs collected in the field.

**Soundsched Analysis – Variable Cover Tool Development**

Subsequent soundsched investigations of the Mayan city of Copán, Honduras (Goodwin et al. 2018b) reestablished the need for a version of the Soundsched Analysis Tool that could account for a variety of land cover types surrounding a site. Copán presents a landscape of ecotones with both vegetative and urban modifications. This case study provided an opportunity to enhance and modify options within the Soundsched Analysis Toolbox. However, the appropriate method of calculating foliage losses had to be determined before the tool could be developed.

As described in the previous chapter, the original Soundsched Analysis Tool models how sound spreads throughout a landscape and is based upon “SPreAD” and “SPreAD-GIS.” Although SPreAD-GIS incorporates some of the formulae contained in the international standards on outdoor sound propagation ISO 9613-1 (1993) and ISO 9613-2 (1996) its treatment of vegetation attenuation is based on an adaptation of SPreAD, which predates the ISO standards. Whereas SPreAD relies on lookup tables to calculate a combined value for Foliage and Ground Cover losses (see Harrison et al. 1980: A-12
Table 8), ISO 9613-2 “Annex A.1 Foliage” follows a curved path radius method of calculation (1993). SPreAD’s lookup tables include attenuation values for conifers and hardwoods which are to be applied at all frequency spectra, and attenuation values for grassland/ open brush at variable levels based on frequency spectra. Each of these attenuation values was to be applied based on the distance between the source and receiver locations (Harrison et al. 1980: A-12). In contrast, although the ISO method is also distance based, it does not differentiate by cover types, instead making the assumption that foliage is dense enough to block views between the sound source and receiver (ISO 1993:16). As a result, the ISO maximum vegetation loss rate exceeded SPreAD’s calculations by approximately 10 dB.

After a review of various methods for calculating vegetation attenuation it was determined that the Soundshed Analysis - Variable Cover tool would base its attenuation values on four general categories of vegetation. These cover type categories correspond to formulae used by the US Forest Service (Harrison et al. 1980; Reed et al. 2009, 2010) and were further informed by the work of Aylor (1972). Category A consists of open or cleared areas (approximately 80% cleared or greater). These areas may include open water, barren soils, open urban or anthropogenically modified spaces, low grasses, crops, and shrubs (<0.5 m tall). Category A areas may include trees or other tall vegetation but these are sparse and do not result in major breaks in line of sight between the sound source and observer; structures or other features are visible on the landscape beyond. Category B areas correspond to denser (approximately 50-80% cleared) vegetation between 1.3-2.0 m tall (e.g., thick maize). This vegetation is not much taller than a person,
however, the average person would have a difficulty seeing through it as visibility is restricted by dense stems. Category C and D areas both consist of dense forested areas (<50% cleared) that a person cannot see through. Type C areas consist of dense coniferous vegetation or "old growth" forests where attenuation is primarily due to tree trunks causing breaks in the line of sight. Type D areas consist of full growth trees with a high density of branches, leaves, and undergrowth. These areas provide the greatest amount of attenuation.

Interestingly, the initial release of the Soundshed Analysis Tool, paralleled the development and release of "Sound Mapping Tools" (SMT) created by the team who developed SPReAD GIS. SMT included aspects of SPReAD-GIS and ISO 9613-2 as well as “Noise Model Simulation” or NMSimGIS created by Ikelheimer and Plotkin in 2005 (Keyel et al. 2017:56-7). Among other improvements, the SMT team revisited their methods of calculating vegetation attenuation and updated the associated Python code. The Python code used in the Variable Cover tool was compared to, and in some cases draws upon, solutions used in SMT.

The Soundshed Analysis – Variable Cover Tool beta release version 0.9.3 script follows a nine step process:

1. **Preparation of Datasets**: While the majority of the inputs used in the Soundshed Analysis Tool can be obtained from literature searches or existing elevation

27 It is interesting to note that the SMT team came to the same conclusions regarding wind effects as I did, and by strange coincidence, Keyel et al. (2017) was received by the same publisher within one day of Primeau and Witt (2018).
datasets following the processes described in the previous chapter for the Soundshed Analysis Tool, the Variable Cover tool requires at least two user-created GIS datasets to function: the Ambient Sound Pressure raster, and the Vegetative Cover Type raster.

a. The Ambient Sound Pressure layer can be created two ways:

i. For a single ambient throughout the study area, the standard ArcGIS tool “Create Constant Raster” should be used. The “Constant Value” should be set to the ambient SPL, and the spatial projection and “Output Cell Size” should match the resolution of the elevation dataset which will be used for modeling. Optionally, the output extent can be set to the output extent of the elevation dataset.

ii. In a landscape where the ambient varies, the user should first create a Polygon feature class using the same spatial projection as the elevation dataset which will be used for modeling, and divide up the study area into polygons accordingly. The feature class must include an attribute field named “VALUE” containing the ambient SPL for each polygon as an integer value. As an example, polygons may represent different vegetative cover types. The Polygon layer is then converted to a raster dataset using the standard ArcGIS tool “Feature to Raster” and specifying “VALUE” as the conversion “Field.”

b. The Vegetative Cover Type layer can also be created two ways:

i. If the polygons created for the Ambient Sound Pressure layer are
based on vegetative cover types (i.e., the area and locations of the polygons within the two datasets are spatially identical) then the user can add an attribute field named “VEGTYPE” to the existing raster. Each polygon would be assigned a vegetation type A-D using the categories as described above. In this case, the same raster dataset would be specified for both dropdown box locations (“Ambient Sound Pressure Dataset” and “Vegetative Cover Type”) in the Soundshed Analysis – Variable Cover tool graphical user interface.

ii. If a single (constant) ambient dataset is being used or if the ambient and cover type datasets are not spatially identical, the user should first create a Polygon feature class using the same spatial projection as the elevation dataset which will be used for modeling, and divide up the study area into polygons accordingly. The feature class must include an attribute field named “VEGTYPE” containing the vegetation type A-D using the categories as described above. The Polygon layer is then converted to a raster dataset using the standard ArcGIS tool “Feature to Raster” and specifying “VEGTYPE” as the conversion “Field.”

2. **Input of Parameters**: Twelve model parameters are input by the user consisting of a short model name and two categories of data, nine of which are identical to the inputs used in the Soundshed Analysis Tool (see Table 6.1).

   Cultural data describing the source of the sound includes: the study location
saved as a point feature class; the height of the sound source in feet measured between ground surface and the primary location where sound is produced (e.g., the bell of a trumpet, the mouth of a speaker); the SPL of the source (dB); the predominant frequency (Hz) of the sound source; and the distance in feet between the sound source and the location where the SPL of the source was measured.

Table 6.1. Soundshed Analysis Tool v0.9.3 Input Variables

<table>
<thead>
<tr>
<th>Cultural Variables</th>
<th>Environmental Variables</th>
</tr>
</thead>
<tbody>
<tr>
<td>Location of Sound Source</td>
<td>Percentage of Relative Humidity</td>
</tr>
<tr>
<td>Height of Sound Source (ft)</td>
<td>Air Temperature (°F)</td>
</tr>
<tr>
<td>Sound Pressure Level of Source (dBA)</td>
<td>Ambient Sound Pressure Dataset (dBA)*</td>
</tr>
<tr>
<td>Predominant Frequency of Source (Hz)</td>
<td>Vegetative Cover Type (Raster)*</td>
</tr>
<tr>
<td>Measurement Distance from Source (ft)</td>
<td>Elevation Data (mASL)</td>
</tr>
<tr>
<td></td>
<td>Elevation Raster Resolution (Cell Size)</td>
</tr>
</tbody>
</table>

* Uses datasets created in Step 1

All cultural data inputs are identical to those used in the Soundshed Analysis Tool.

Environmental data for the study location includes: the air temperature (°F), and the percentage of relative humidity; the ambient sound pressure level dataset created in Step 1; a vegetative cover type raster created in Step 1; an elevation raster dataset; and the resolution of the elevation raster dataset. With the exception of the two datasets created in Step 1, the environmental data inputs are identical to those used in the Soundshed Analysis Tool.
All eleven inputs and a model name are required to run the model (see Figure 6.1) and must be entered by the user before modeling can begin. Once this step is completed, the user clicks “OK” to run the model and steps 3-8 proceed automatically with no additional user interaction.

**Figure 6.1. Soundshed Analysis – Variable Cover Tool 0.9.3 Graphical User Interface**

3. **Definition of the study area:** The script “clips” out a portion of the elevation dataset within a distance of 3.2 kilometers (2.0 miles) between lines 57-102. During this step the spatial footprint of the study area is also set as the modeling extent for the remainder of the script in lines 84-93.
4. **Calculating distance attenuation**: Both Soundshed tools calculate distance attenuation using the same methods. In the Variable Cover tool this occurs between lines 112-163. The distance attenuation layer is copied from temporary to final outputs and will be renamed during modeling step 8.

5. **Calculating atmospheric absorption loss**: Again, both Soundshed tools calculate atmospheric absorption using the same methods. In the Variable Cover tool this occurs between lines 165-236. Atmospheric absorption loss is saved as a temporary layer only.

6. **Calculating foliage and ground cover loss**: As explained earlier in this chapter, foliage and ground cover losses are based on the density and distance (i.e., linear extent through which sound must travel) of intervening vegetation between the sound source and the receiver (see lines 238-303). Thicker vegetation results in greater sound losses as seen in the coefficients assigned to vegetation categories A through D (see lines 265-268). Vegetation attenuation data is saved as a temporary layer only.

7. **Calculating viewshed, barrier attenuation, and topographic loss**: During this step viewshed is calculated between lines 354-361; barrier attenuation and topographic loss are calculated between lines 305-354, Fresnel number calculation can be found between lines 373-438; and the barrier attenuation formula appears in lines 440-444. This step follows the same methodology as the Soundshed Analysis Tool.
8. **Producing final outputs**: Temporary datasets created in steps three through seven above are used to derive cumulative effects and establish primary impact areas for each form of attenuation based on the soundflow path and associated topography (see lines 446-454 of the python script). Final soundshed model outputs include four layers, identical to the outputs created by the Soundshed Analysis Tool:

a. RA: This layer describes the SPL of the source as heard over the background SPL otherwise known as the “rise over ambient” dBA level (see lines 485-495, 497, 504-505 of the python script);

b. PR: This layer depicts the general sound “propagation” pattern. Hypothetically, if the ambient SPL was 0 dBA this is the extent to which sound would spread in relation to the elevation dataset (see lines 458-483, 494-496, 501-502);

c. SS: This layer, created in step 4, also depicts a hypothetical scenario, “spherical spreading.” This layer would represent distance attenuation if there were no barriers present to block the spread of sound (see lines 494-495, 498, 507-508 of the python script). The results are independent of the elevation dataset;

d. VS: As described in step 7, the tool also created a “viewshed” for the sound source, which is be saved as a final model output during this step (see lines 494-495, 499, 510-511). The viewshed relates to the elevation dataset and height of the sound source.
9. **Symbolizing the data**: Once modeling is complete, the user adds the data to an ArcGIS map, and defines its symbology.

In summary, the Soundshed Analysis – Variable Cover Tool consists of a geometric-type model which assumes sound travels through the air along straight-line paths. Directionality of the source and wave effects, such as reverberation, are not considered by the model. The tool uses formulae of outdoor sound propagation, calculating free-field sound attenuation following ISO 9613-2 (1996), atmospheric absorption loss following ANSI 1.26 (1995), topographic loss following ISO 9613-2 (1996), vegetation loss following Aylor (1972) and SPreAD (Harrison et al. 1980; Reed et al. 2009, 2010), and barrier effects based on Maekawa’s optical diffraction theory (Lamancusa 2009; Maekawa 1968).

**Variable Cover Tool: Exploratory Application**

As described above, the Soundshed Analysis - Variable Cover tool was first applied to research hypotheses within the Maya city of Copán. Details regarding that research and its conclusions are presented as a case study appearing in Chapter 8. However, prior to the initial application of the tool, exploratory testing and model debugging occurred using a series of hypothetical scenarios based on existing modeling locations and Soundshed Analysis Tool results. What follows is a focused technical discussion comparing the estimated soundsheds generated for minor variations of the same acoustic scenario but utilizing the different soundshed tools.

Figure 6.2, originally appearing in Goodwin et al. (2018b), shows the spread of sound created by a conch shell trumpet as it was played at Point 6 during the acropolis
procession of Ruler 13. This figure was created with the original Soundshe Analysis Tool. The Urban DEM shown on the map and utilized for soundshed modeling includes the elevations of structures extant during Ruler 13’s reign (695-738 CE). Figure 6.2 is presented for comparison with Figures 6.3 through 6.6; the latter group of images were created with the Soundshe Analysis - Variable Cover tool.

**Figure 6.2.** Estimated soundshed of a shell horn played from the East Court (Point 6) at an Acropolis Procession during the reign of Ruler 13.
Figure 6.3 represents the spread of sound from procession Point 6 at a constant ambient Sound Pressure Level (SPL) of 31 decibels (dBA). It is presented at a smaller scale than Goodwin et al.’s (2018b) image (Figure 6.2). Figure 6.4 represents the same modeling scenario but includes a visualization of the land cover layer. The land cover layer, created by Heather Richards-Rissetto, was broken down into vegetation categories as shown in Table 6.2.

**Figure 6.3.** Estimated soundshed of a shell horn played from the East Court (Point 6) at an Acropolis Procession during the reign of Ruler 13 [Created using the Variable Cover Tool at a Single Ambient dBA]
**Figure 6.4.** Estimated soundshed of a shell horn played from the East Court (Point 6) at an Acropolis Procession during the reign of Ruler 13 [Created using the Variable Cover Tool at a Single Ambient dBA, shown with Land Cover Types]

<table>
<thead>
<tr>
<th>Soundscape Extent of a Conch Shell Trumpet During the Acropolis Procession (Ruler 13)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Inputs</strong></td>
</tr>
<tr>
<td>Sound Source Height: 6ft.</td>
</tr>
<tr>
<td>Frequency: 330 Hz.</td>
</tr>
<tr>
<td>Sound Level of Source: 96 dB</td>
</tr>
<tr>
<td>Measurement Distance: 1ft.</td>
</tr>
<tr>
<td>Temperature: 79 F.</td>
</tr>
<tr>
<td>Relative Humidity: 90%</td>
</tr>
<tr>
<td>Ambient SPL: 31 dB</td>
</tr>
<tr>
<td>Elevations: Ruler 13</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Legend</th>
</tr>
</thead>
<tbody>
<tr>
<td>Procession Waypoints</td>
</tr>
<tr>
<td>Audible Area (R.13)</td>
</tr>
<tr>
<td>Structures</td>
</tr>
<tr>
<td>Sound Pressure Level (dB)</td>
</tr>
<tr>
<td>High : 54.679</td>
</tr>
<tr>
<td>Low : 0</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Landcover Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>water</td>
</tr>
<tr>
<td>urban</td>
</tr>
<tr>
<td>low terrace</td>
</tr>
<tr>
<td>intermountain pocket</td>
</tr>
<tr>
<td>high terrace</td>
</tr>
<tr>
<td>foothills</td>
</tr>
<tr>
<td>floodplain</td>
</tr>
</tbody>
</table>

![Map showing estimated soundshed of a shell horn played from the East Court (Point 6) at an Acropolis Procession during the reign of Ruler 13, with inputs and landcover types indicated.](image)
Table 6.2. Land Cover Vegetation Categories and Ambient SPLs

<table>
<thead>
<tr>
<th>Land Cover Type</th>
<th>Vegetation Attenuation Category</th>
<th>Variable Ambient (dB)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Water</td>
<td>Category A</td>
<td>30</td>
</tr>
<tr>
<td>Urban</td>
<td>Category A</td>
<td>30</td>
</tr>
<tr>
<td>Low Terrace</td>
<td>Category A</td>
<td>30</td>
</tr>
<tr>
<td>Intermountain Pocket</td>
<td>Category C</td>
<td>25</td>
</tr>
<tr>
<td>High Terrace</td>
<td>Category C</td>
<td>25</td>
</tr>
<tr>
<td>Foothills</td>
<td>Category B</td>
<td>22</td>
</tr>
<tr>
<td>Floodplain</td>
<td>Category A</td>
<td>20</td>
</tr>
</tbody>
</table>

Figure 6.5 was created using ambient SPLs which varied according to the land cover type. For testing purposes these SPLs in the mid 20’s were arbitrarily based on values from Reed et al. (2010) and may be lower than actual ambient SPLs (see Table 6.2). Figure 6.6 represents the same modeling scenario as Figure 6.5 but is shown with a visualization of the land cover layer. The same series of four maps (following Figures 6.3-6.6) were produced for points 1 and 7 on the Acropolis Procession as well. These estimated soundsheds can be seen in Appendix C.
Figure 6.5. Estimated soundshed of a shell horn played from the East Court (Point 6) at an Acropolis Procession during the reign of Ruler 13 [Created using the Variable Cover Tool at a Variable Ambient dBA]
Figure 6.6. Estimated soundshed of a shell horn played from the East Court (Point 6) at an Acropolis Procession during the reign of Ruler 13 [Created using the Variable Cover Tool at a Variable Ambient dBA, shown with Land Cover Types]

The most noticeable differences between the soundsheds created using the Variable Cover tool and the Goodwin et al. (2018b) image created with the Soundshed Analysis Tool are the pockets of higher SPLs occurring within certain combinations of cover types and ambient SPLs, such as the red linear patches of high SPLs seen directly south-southeast of Points 7 and 8 in Figures 6.5 and 6.6 that correspond with the “floodplain” areas seen in Figure 6.6 which had a low ambient SPL, and the ability to hear
the sound of the conch over the lower ambient background sound within the foothills to
the north and south of the Acropolis. These observations indicate the importance of
understanding what acoustical formulae the model is applying, and correctly defining the
appropriate cover type in a replicable manner. In a direct application of SPreAD-GIS
modeling techniques, only the structures would have been defined as “urban,” however,
the Soundshed Analysis – Variable Cover tool takes into account that the “low terrace”
area surrounding these features was also anthropogenically modified. The different levels
of clearing or cover type conversion considered by the Soundshed Analysis - Variable
Cover tool are, therefore, divided in such a way as to be applicable to a broad range of
past conditions, rather than a focus on “development” in the modern urban planning
sense.

The data used with the “Soundshed Analysis - Variable Cover” tool can come from
a variety of sources. User-defined data can be created by collecting SPLs of various
ecological zones in the field, past vegetation reconstructions, literature searches (for both
SPL and/or land cover information) or any combination of these methods. Land cover
could also be derived from modern data such as the National Land Cover Dataset or via
other remote sensing applications. The correct modeling tool must be selected by the
researcher based on their expert knowledge of the study area as well as their ability to
accurately represent past conditions for modeling. It is suggested that the Soundshed
Analysis – Variable Cover tool be applied to study areas where the ecology within a 3-4
kilometer radius exhibits a higher degree of diversity.
Chapter 7. Case Study 1: Ancestral Pueblos in Chaco Canyon

In the Southwestern United States, ceremonialism was such an intrinsic feature of the Ancestral Puebloan polity that some researchers have adopted the term “rituality” to describe the sociopolitical organization associated with those who constructed Great Houses in and surrounding Chaco Canyon, New Mexico (Judge and Cordell 2006:197; Reed 2004:36). By the ninth century, periodic ritual activities such as feasts and dances were drawing people to the canyon at regularly defined intervals, following a calendar developed through astronomical observations. Research suggests that while heterogeneous populations converged in this area from multiple directions, participation in ceremonialism through sodalities allowed for cooperation and inclusive communities (Judge and Cordell 2006:194-7). Although the earliest construction within the canyon began in the ninth century CE, the Chaco culture area (see Figure 7.1) reached its peak population, broadest geographic distribution, and the height of organizational complexity in the eleventh and twelfth centuries CE (Lekson 2006:3; Reed 2004: xxx, 1).

As Lekson et al. have succinctly stated: “Chaco is Great Houses (2006:93).” Today, the contemporary Chaco Culture National Historical Park, a UNESCO World Heritage Site, draws approximately 50,000 people annually28 to see the architectural remains of Chaco great houses, and perhaps for them to experience travelling between

28Based on an average count of annual recreation visitors from the years 2000-2019 (52,279 people annually). Visitor counts for the Chaco Culture National Historical Park from the year 1925 to 2021 are available online at https://irma.nps.gov/STATS/Reports/Park/CHCU.
great houses and other cultural sites within the park as well. Twelve great house sites are located throughout the canyon. These sites feature distinctive masonry as well as an evolution of building techniques over time and required a large organized workforce to construct (Lekson et al. 2006:78-82). Pueblo Bonito, the largest Great House, was a four-story D-shaped structure measuring approximately 1.2 ha (90 x 150m) in size (Lekson 2006:10-1; Witt and Primeau 2019:4-5). Great House construction and organization often reflect Chacoan ideology, including: an emphasis on balanced dualism; the symbolism of
horizontal and vertical dimensionality tied to a central place (cardinal directions and upper/lower worlds their cosmographic analogs); cyclical renewal (e.g., redecoration or episodic destruction/reconstruction); and the path or journey (Van Dyke 2008:48-58). It is estimated that only 5% of the people within the Chaco region lived in Great Houses; for example Pueblo Bonito appears to have supported approximately 37 households, leading to interpretations that Great Houses served largely as civic-ceremonial structures (Lekson et al. 2006:92-3). In addition to Great Houses, the Chacoan cityscape featured earthworks such as berms and platform mounds, which sometimes featured staircases and masonry facing; roads built wider than necessary for simple transport needs (often nine meters across); and Great Kivas, large (20 meter diameter) single room subterranean structures – all of which were associated with ceremonialism (Lekson 2006:12-13; Lekson et al. 2006:104-8; Reed 2004:46-7, 72).

When approaching the landscape through the combined frameworks of phenomenology, performance theory, and political theater, it becomes clear that the elites guiding construction at Chacoan sites were not only building architecture, but fashioning stages which served to legitimize their roles and reify political power in the 10th and 11th century CE. The built landscape within Chaco Canyon directed movement between sites, afforded intervisibility between natural and anthropogenic features, and likely contributed to social memory (Van Dyke 2008:41-7). Great Houses and Great Kivas were locations of power, and embodied Chacoan ideology, while shrines and stone circles, which often mark sacred locations and topographical high points, have been described as “repeater stations” for connecting lines of site between significant
places (Brown 2014:56; Lekson 1999, 2008; Van Dyke 2008:58,142). To better understand the extent of performance spaces, the Soundshed Analysis Tool was used to investigate the interaudibility\(^{29}\) of sites within Chaco Canyon to determine:

1. Can performance spaces be identified within the landscape? (i.e., where could specific outdoor events be heard?)

2. Are sites located in areas that marked the boundaries of performance space? (i.e., does the built environment provide evidence that audibility may have played a factor in site placement?)

As Crabtree et al. describe when discussing performances within the Indigenous Southwest: “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 (2017:77).” “Spectacles also incorporated participants outside the confines of the kiva walls through sound, adding to their scope (Crabtree et al. 2017:77).” The Soundshed Analysis Tool provides a unique opportunity to investigate these sonic hypotheses and bring a new dimension to our understanding of ritual and political performance at these sites.

\(^{29}\)The term “interaudibility” as used within this dissertation is similar to the term “intervisibility” and describes the ability for sound to be heard between sites. Recall that, as described in Chapter 4, audibility should not be confused with speech intelligibility, though the terms are not necessarily mutually exclusive.
Sound and Ceremony in the American Southwest

Music, dance, and other sound producing events were an integral part of ritual and ceremony in the American Southwest as evidenced by ethnographic analogy. This is echoed by the fact that flutes, trumpets, and other instruments recovered from Chacoan Great Houses were often found in association with or even decorated by imported trade goods holding ceremonial significance, including turquoise, pottery, censors, and macaw skeletons (Brown 1971:365-6; Mills and Ferguson 2008:346). Many of these objects, and other exotica, such as shells, cacao, and copper bells, have been interpreted to reveal a connection with Mesoamerican Flower World cosmology and symbolism (Weiner 2015:221-4). Flower World cosmology is often expressed through sound or performance and involves multimodal sensory expression, i.e., linkages of colors, smells, and sounds (Brown 2014:59-60; Hays-Gilpin et al. 2010; Weiner 2015:224, 231).

Although the details of Chacoan ritual are unknown, instruments and other ritual objects continue to be used by post-contact and contemporary inhabitants of the region, many of which have oral histories of the Canyon and surrounding areas. The Hopi and Zuni both make use of the conch shell trumpet as the voice of the Plumed Serpent in the Paalöloqangw and Kolowisi ceremonies, respectively. Portions of each of these ceremonies take place within kivas, the Paalöloqangw ceremony in particular taking place during the winter solstice and again in February. Although both traditions hold that the Plumed Serpent originally came to punish people for immorality, the Plumed Serpent can also control the rain and severe weather, ultimately helping people by providing water for crops and tempering storms (Brown 2005:294-7; Mills and Ferguson 2008:341-3, 345;
Creation stories of both the Hopi and Navajo associate flutes and flute playing with emergence into this world, and iconographic depictions of flute players in the southwest may date to 400 CE or earlier (Brown 2005:163; Taube 2010:73, 76-9; Weiner 2015:234). Foot drums, known to be used at Acoma and Hopi, may also have been used in Chacoan Great Kivas by overlaying floor vaults with wooden planks to create a loud dancing surface (Brown 2009:46; Van Dyke 2007:125; Weiner 2015:237). Foot drums are also associated with emergence through a sipapu, a hole connecting a lower world to this one – “considered to be the navel of the earth and represent the center of the cosmos (Brown 2014:49, 52, citing Ortiz 1972:142; Taube 2010:76-9). Contemporary Pueblo ritual incorporates drums, rattles, other instruments, and a variety of vocalization styles (e.g., song, chant) (Van Dyke 2007:125, 2015:90; Weiner 2015:237).

As described by Donald Brown, the sound producing devices within the indigenous Southwest fall into the Hornbostel-Sachs classifications of idiophones30 and aerophones31 (1971:364). Though ethnographic accounts from the region include the historic use of membranophones32 (i.e., drums featuring a stretched membrane), only plank drums (idiophones) appear in the early Indigenous archaeological record (Brown 2005:307). In addition to plank drums the idiophones include various rattles, wood or bone tinklers, copper bells, percussion stones, and rhasps, while the aerophones consist of

30 “Idiophones: The substance of the instrument itself, owing to its solidity and elasticity, yields sounds, without requiring stretched membranes or strings (Hornbostel and Sachs 1961:14).”

31 “Aerophones: The air itself is the vibrator in the primary sense (Hornbostel and Sachs 1961:24).”

32 “Membranophones: The sound is excited by tightly-stretched membranes (Hornbostel and Sachs 1961:17).”
various whistles and flutes made of clay, bone, or reeds, bull roarers, and shell trumpets (D. Brown 1971:364; E. Brown 2005).

At Pueblo Bonito, eight of the 11 flutes found were associated with burials in Room 33, while that room also contained one Strombus shell trumpet. At least 16 additional shell trumpets were recovered from Rooms 6, 10, 13, 17, 38, 42, 90, 97, and 201; and Kivas A and R (D. Brown 1971:365-6; E. Brown 2005:298-301, 2014:50-52; Loose 2012:129; Mills and Ferguson 2008:346; Weiner 2015:233). As described above, all of these instruments were discovered in association with other ritually charged materials. The shell trumpets recovered from Chaco Canyon represent the earliest use of these instruments in the Southwest, dating from approximately 900-1150 CE (Mills and Ferguson 2008:346). Shells recovered from the southwest are likely to have originated in the Gulf of California. Strombus and Murex shells were most commonly used as trumpets, though other genera have also been used for this purpose (Brown 2005:293; Loose 2012:128; Mills and Ferguson 2008:346). Mills and Ferguson suggest that ritual specialists may have personally travelled to the Gulf to procure the shells as a demonstration of their leadership abilities (2008:350-1; Weiner 2015:222).

Direct evidence for the importance of sonic performance in both the archaeological and ethnographic record is also illustrated by Tse Biinaholtsa’a Yalti, an amphitheater located along the face of Chaco Canyon, between the Chetro Ketl and Pueblo Bonito Great Houses. Navajo for “concavity in the rock that speaks,” this feature is: associated with a story “about Diné (Navajo) siblings who receive special instructions concerning chants and tones;” it is a portal to a divine dimension, and is the center of a Navajo
ceremony *Chiihwojoolye of Tsebiinaholts’a Yalti* which features the use of a conch shell trumpet (Loose 2008:32-3, 2012:2; Stein et al. 2007:206). The canyon wall comprising the amphitheater curves more steeply vertically than horizontally at an approximate 3.7:1 ratio. Within the feature’s natural arc is a 60m long, 3m high, and 2m deep alcove created through the removal of bedrock. The alcove is also associated with a rock art panel (29SJ1931) and altar (Stein et al. 2007:206-8). A series of acoustic studies carried out at the amphitheater featured: sine sweeps and spectrum analysis (both within and directed towards the amphitheater); continuous tone broadcasts combined with subject centered survey; and recordings of sounds created by a human voice, Native American flute, and conch shell trumpet. Acoustic effects noted during these studies included flutter echoes, standing waves, and focal properties of the amphitheater (Loose 2008:37-9, Stein et al. 2007:206-8).

**Methods of Investigation: Modeling Inputs and Scenarios 1-3**

The Soundshed Analysis Tool was used to model the estimated propagation of sound at 33 sites within the Chacoan landscape consisting of 13 great house locations, 1 great kiva, 5 shrines, and 14 stone circles (see Figure 7.2). Modeling locations were collocated with notable landscape features, such as the location of the ponderosa pine in the west court at Pueblo Bonito, or the triwall feature at Pueblo del Arroyo, when data was available for these locations. Ruth Van Dyke of Binghamton University and Kyle Bocinsky of Crow Canyon Archaeological Center provided locational data for Chacoan
Figure 7.2. All Study Locations within Chaco Canyon

sites. LiDAR data for Chaco Canyon (1.5 meter resolution) was obtained from Open Topography (2016). Three scenarios were chosen to represent auditory phenomena that were likely to have been part of the Chacoan experience, including (1) the murmur of people speaking softly to one another, as can be heard when people are assembling together in a group, (2) the sound of an individual with their voice raised in order to be heard by a crowd or audience, and (3) the sound of a conch shell trumpet, as evidenced by material remains and ethnographic records discussed previously. Given the
importance of astronomical events and the existence of a ritual calendar, modeling inputs required to explore these scenarios were gathered for sunrise and solar noon on the summer solstice (Judge and Cordell 2006:194-7; Sofaer 1997; Van Dyke 2008:56-9).

Paleoclimatological records indicate that the regional climate has been generally stable within the past 10,000 years (Dean 1988; Hall 1988; Larson et al. 1996; Larson and Michaelsen 1990), therefore, historic average air temperature and relative humidity data was used as a proxy. For June, this meant utilizing an average relative humidity of 30%, and a low temperature of 13° Celsius (55.4° Fahrenheit) to represent sunrise on the summer solstice, or a high temperature of 32° Celsius (89.6° Fahrenheit) to represent the afternoon of the summer solstice (Western Regional Climate Center 2011). All modeling scenarios assumed that ambient noise levels within the valley measured 20.7 dBA, the background noise levels measured for pinyon-juniper shrubland (Ambrose 2006).

Source sound levels, frequencies, and measurement distances were obtained through a literature search. As noted by Brown, ethnographic evidence indicates shell trumpets were typically played without accompaniments, making them ideal for modeling purposes (2005:291). Due to Richard Loose’s previous work regarding the use of conch trumpets within Chaco Canyon, the measurements he obtained from a reproduction conch shell trumpet were used as modeling inputs. Loose obtained a *Strombus galeatus* shell within the appropriate size range of Ancestral Puebloan trumpets as reported by E. Brown (2005) and created a blowing aperture comparable to that of Pepper’s (1909) Burial 14 trumpet (Loose 2012:130-1). Using digital recording and analysis software
Loose determined that the recreated trumpet had a fundamental tone of 329.84 Hertz and a sound pressure level of 96 decibels when blown into, or a natural resonance of 330.0 Hz when subjected to an impulse test, therefore, these modeling inputs were used for a shell trumpet at a measurement distance of one foot (Loose 2012:131). As conch trumpets were likely to have been played by elites, the sound source height (i.e., the individual’s height plus the horn length) was assumed to be 1.8 meters (six feet) above ground for modeling purposes.

Hayne et al. (2006) and Lazarus (1986) provided the source sound levels, frequencies, and measurement distances for both crowd noise and an individual addressing a crowd. Hayne and colleagues describe two facets of crowd noise: “a babble due to multiple, simultaneous, random conversations; and transients due to events such as people laughing, yelling, or cheering (Hayne et al. 2006:236).” As this modeling scenario sought to replicate the sounds experienced as a crowd gathered for an event, the former descriptor or “relaxed speaking” was used for modeling purposes, providing modeling input measurements of 48 dBA when measured at 1 meter (Hayne et al. 2006:237; Lazarus 1986:454). To be heard and understood over the sound of a crowd, an individual must raise their voice when speaking. Although it is possible for a man to achieve a “maximal shout” with an SPL of 96 dBA, this level cannot be maintained for a prolonged period of time, nor does this produce reliably intelligible speech. A “shout” of 84 dBA when measured at 1 meter was, therefore, used to represent an orator with a raised voice addressing a crowd, though recent studies have shown that this number
may represent a conservative estimate\textsuperscript{33} (Lazarus 1986:453-5). For both crowd noise and an individual addressing a crowd the height of the sound source (i.e., speakers’ mouths) was assumed to be 1.5 meters (5 feet).

Although soundshed modeling was initially completed for crowds gathered at various locations throughout Chaco Canyon (see Figure 7.3)\textsuperscript{34}, the results were determined to be too speculative for a number of reasons. First, the Soundshed Analysis Tool works with point source data, however, a crowd is not a single point source, but rather a series of point sources clustered together. While it is possible to model a number of individual points representing positions within a crowd, cumulative sound levels grow logarithmically not arithmetically, therefore, a Cumulative Soundshed Tool is under development to overcome this limitation\textsuperscript{35}. Second, more accurate crowd sound formulae are based on the number of people composing the crowd as well as other factors such as: predominant sex of the group of speakers; whether alcohol or other mind altering substances could presumably be effecting the speakers; and directional orientation of the speakers (Hayne et al. 2006:236-9). While it is certainly possible to attempt to reconstruct the exact circumstances leading to the gathering and composition of a crowd, the modeling limitations combined with the relatively limited spread of crowd noise rendered

\textsuperscript{33} Boren et al. have reported that for both male and female trained speakers, average “maximal speech (defined as the loudest achievable without shouting or screaming)” levels are just over 90 dBA at a measurement distance of 1 meter (2013:3).

\textsuperscript{34} Note that Appendix D contains additional modeling results for all scenarios, but does not duplicate the images specifically discussed in this chapter.

\textsuperscript{35} Though under development, the Cumulative Soundshed Tool is beyond the scope of this dissertation. When complete it will be released in a future update to the Archaeoaoustics Toolbox.
Figure 7.3. Estimated Soundshed of Crowds at Various Locations within Chaco Canyon at Noon on the Summer Solstice

this modeling scenario negligible for investigating site interaudibility, though there are numerous other research questions for which this modeling approach would be appropriate.

Scenario two investigated the propagation of sound from an individual with a raised voice, in this case a male speaker addressing a crowd. Pueblo Alto and New Alto are two Great Houses located approximately 150 meters (494 feet) from each other on the mesa top north of Chaco Canyon. Figures 7.4 and 7.5 show the estimated spread of
sound from the speaker’s location at noon on the summer solstice, with a maximum sound level of approximately 57.5 dBA above the background sound in locations nearest the speaker. These figures illustrate not only the interaudibility between the Great Houses, but also the barriers to the propagation of sound caused by the architecture. For example, Figure 7.5 shows that Pueblo Alto’s architecture would prevent an individual located within the Great House, or east of the Great House, from
As described above, the built environment surrounding Chaco Great Houses also included platform mounds, such as those located in front of Pueblo Bonito. These mounds were rectangular adobe-faced structures with staircases climbing approximately 3-4 meters tall. The mounds were primarily constructed from household deposits, but also
contained evidence for feasting and deposits of exotic goods such as cacao, turquoise, macaw remains, and Narbona Pass chert. Flat surfaces on top of the mounds presented a “stage” from which elite orators could address people gathering below (Lekson 2007:39; Lekson et al. 2006:104-5; Witt and Primeau 2019:5). Ruth Van Dyke states: “Standing atop them, with the great house and the north face of Chaco Canyon towering behind, ritual leaders would have been a very impressive sight. Ceremonies performed atop the mounds would have been highly visible to masses of people who, perhaps, did not have access into the great house itself” (2008:130).

Figure 7.6 shows the estimated soundshed of the orator’s voice rising 58 decibels (dBA) above ambient, encompassing multiple sites throughout the canyon, notably Casa Rincoñada (10), Chetro Ketl (8), Pueblo del Arroyo (6), and the 29SJ1572 stone circle. This indicates that an event at the platform mound was not just meant to be experienced in front of Pueblo Bonito, but throughout Downtown Chaco. Therefore, the entirety of Downtown Chaco, and not just Pueblo Bonito’s plazas, can be viewed as a performance space for such an event. Furthermore, Figure 7.6 illustrates the amount by which the sound rises over ambient noise levels, indicating a positive signal-to-noise ratio. While speech intelligibility wasn’t initially approached as a specific topic of investigation here, work by Alvarsson et al. (2014) has shown that the signal-to-noise ratio is highly correlated to the Speech Intelligibility Index (SII) and may be used as a proxy of the SII outdoors.
Using the signal-to-noise ratio as a proxy for SII, the 5 dBA contour, would equate to an approximate SII of 0.6 in a free field according to modeling conducted by Larm and Hongisto (2006:1116, Figure 12). Additionally, Lazarus (1986:440 Figure 1) and Jovičić...
(1991:58, Figure 5) indicate that a signal-to-noise ratio of 5 dBA would equate to an approximate speech intelligibility (SI) score greater than 80 and 85 percent, respectively. Therefore, Figure 7.6 also indicates the extent to which an individual’s speech may have been understood over environmental background noise given an absence of intervening noise sources, illustrating an approximate degree of speech intelligibility at the Pueblo Bonito (7), Pueblo del Arroyo (6), and Chetro Ketl (8) great houses, as well as the Casa Rinconada great kiva (10). Additionally, people at Kin Kletso (5) may have been able to hear the individual if they listened carefully for the sound of his voice, but likely would not have been able to understand what he was saying, as Kin Kletso is located beyond the contour indicating the SII of 0.6.

Scenario three investigated the propagation of sound from a conch shell trumpet played at sunrise on the summer solstice. Returning to the position atop the platform mound at Pueblo Bonito, the estimated sound propagation reveals that a trumpet would have produced a sound approximately 60 dBA above background noise levels. Figure 7.7 clearly illustrates that individuals at Kin Kletso, Pueblo del Arroyo, Casa Rinconada, and Chetro Ketl, would have heard a conch shell trumpet blown on the platform mound at Pueblo Bonito indicating again that events at the mound were not just meant to be experienced in front of Pueblo Bonito, but throughout Downtown Chaco. By instead producing sounds through a horn rather than the human voice (all other environmental factors remaining constant) the soundshed increases by approximately 299.4 meters (982.3 ft., see Figure 7.8) encompassing more of the landscape.
Figure 7.7. Estimated Soundshe of a Conch Shell Trumpet Played from the Platform Mounds at Pueblo Bonito at Dawn on the Summer Solstice
**Figure 7.8.** Comparison of the Estimated Soundshed Extents of a Conch Shell Trumpet and Elite Orator from the Platform Mounds at Pueblo Bonito at Dawn on the Summer Solstice.
Figure 7.9 shows the estimated soundshed of an individual blowing a conch shell trumpet immediately outside Casa Rincoñada, the largest kiva in the Puebloan world. Modeling indicates that various shrines and circles may have been placed in liminal locations for such an occasion. Circles 29SJ1976A_F and 29SJ2240 are located on the very edge of the soundscape, and the shrine 29SJ1207 may have marked not only a high point on the landscape, but also the location where an individual may first have heard rituals on the canyon floor as they approached from the south. This provides evidence that these structures may have been intentionally placed on liminal locations on the landscape, marking the space between sacred and profane where people could begin to actively participate and experience a ritual occurring at Casa Rincoñada. Though difficult to prove, this potential intentionality may be similar to that displayed by the creators of Paleolithic rock art, whose images were determined to have been placed in locations of high resonance, albeit at a much larger scale (Reznikoff and Dauvois 1988; Scarre 1989; see also Watson 2006; d'Errico and Lawson 2006:53-55 for a discussion of intentionality).
Figure 7.9. Estimated Soundshed of a Conch Shell Trumpet Played from Outside Casa Rincoñada at Dawn on the Summer Solstice
Methods of Investigation: Scenario 4

As the results of modeling Scenarios 2 and 3 indicate, performance spaces can be identified within the landscape. The complete set of modeling results (Figures in this chapter, and Appendix D) depict that sites were often located in areas that marked the boundaries of performance spaces. Given this, Scenario 4 asks if sonic evidence further supports Brown’s hypothesis that shrines and stone circles served as “repeater stations” for connecting significant places through interaudibility (2014:56).

Using modeling data generated for Scenario 2, Scenerio 4 considered the complete interaudibility between all 33 site locations for an elite orator making a public address. The ESRI ArcGIS tool “Extract Multi Values to Points” was used to query the soundshed rasters at each site location, and sound pressure levels were returned in a table which was exported to Microsoft Excel. Interaudibility was then classified into four categories, Potentially Speech Intelligible (SI); Actively Audible (A); Likely Audible (L); and Inaudible (null), as follows (See Appendix D, Table D-1):

**Potentially Speech Intelligible (SI):** Sound pressure levels between these sites were equal to or greater than 5 dBA, equating to an approximate speech intelligibility (SI) score greater than 80 to 85 percent;

**Actively Audible (A):** Sound pressure levels between these sites were audible, but less than 5 dBA, indicating that a person would need to be actively listening to hear the sound, and speech may not have been intelligible;

**Likely Audible (L):** Although the estimated soundsheds generated by the model indicated null results, expert judgement and review of the resulting soundsheds indicates that these sites would likely be within audible range of...
each other. Factors such as the point chosen for a modeling location (particularly in cases where sound was modeled from inside a plaza), and intervening modern intrusions in the LiDAR data (e.g., roads) appear to have impacted the resultant soundsheds. In addition, the distinction between raster resolution (i.e., site size represented electronically as a single point) and known site spatial extents were considered. An extremely conservative approach was taken when assigning category (L); and 

Inaudible: The estimated soundsheds generated by the model indicated no change in the ambient decibel level (i.e., null results).
Figure 7.10. Interaudibility of Sites Located within the Northwestern Portion of Chaco Canyon

Interaudibility data was used to create a connection table (See Appendix D, Table D-2), then mapped in GIS using ESRI’s “XY to Line” tool resulting in 33 interaudibility lines between sites. Only seven of the 33 site locations modeled were acoustically isolated from others within the dataset (Shrines 29SJ2384 and 29SJ706; and Stone Circles 29SJ1326, 29SJ1419, 29SJ1474, 29SJ1660, and 29SJ1976A_F), and all Great
Houses and Great Kivas within the dataset experienced some interconnectivity (see Figures 7.10 through 7.12).

The audibility line between 29SJ1572 and 29SJ2240 which connects clusters of Great Houses in the canyon below with those located on the mesa above (see Figure 7.12) provides some evidence that shrines and stone circles could serve as repeater stations. However, many of these lines are in the active audibility range indicating
vocalizations would require an actively listening observer to be heard, and would function only as audible signals (i.e., sound audible, but speech unintelligible). The range of these signaling connections would likely have been increased when using an instrument with a higher sound pressure level, such as a conch shell trumpet, as a signaling device. It appears much more important that great houses themselves be located within the speech intelligibility range of other sites. Overall, only five of the 33 connections did not include a Great House or Great Kiva within audible site pairs.
Model Assumptions

I reiterate here that as indicated in the modeling inputs section above, estimated soundsheds were created using assumed numbers, and ideally model variables would utilize sound properties measured by a researcher. Additionally, LiDAR datasets present topographic data from a specific point in time, and, therefore, without manually adjusting or correcting the terrain before modeling, the Soundshed Analysis tool can only create output based on that contemporary LiDAR data. The modeling of sound at Chacoan sites as discussed in this chapter presents the propagation of sound across the modern landscape. Anachronisms include not only obviously modern features such as buildings or the road present in Figures 7.6 through 7.9 seen as a curvilinear feature wrapping around the south of Pueblo Bonito, but also the locations of shrines, stone circles, and great houses which may not have been contemporaneous or socially significant during the same occupation periods. As Van Dyke states, “past landscapes no longer exist—contemporary landscapes can provide researchers with only partial, distorted experiences” (2008:39). Researchers must work to identify and mitigate such limitations, and bear in mind that these are models: representations of reality that help inform our understanding of past experience.

Discussion and Future Directions

In a place such as Chaco Canyon where Great Houses required a large labor force to construct, but where the remains of material culture suggest asymmetries between elites and non-elites, or between competing groups of elites, political theater would have served to create, manipulate, and reinforce power relations within the community. Construction of specialized structures for ritual performance, such as the
Pueblo Bonito platform mounds, Tsebiinaholts’a Yalti, and Chacoan roads all indicate that political theater was meant to be experienced. Inclusion in the ritual at Chaco incorporated all the senses: viewing (e.g., specialized architecture, color symbolism); tasting (e.g., Cacao); hearing (e.g., conch trumpets, Tsebiinaholts’a Yalti); movement (e.g., roads, dance); and memory/knowing (e.g., items purposefully sealed within kiva walls, rituals performed for select groups within kivas). By creating soundshed maps, this research presents the geographic extent of these performance spaces as bounded by sounds propagated outdoors.

This case study presents an early step in the archaeoacoustic exploration of landscapes. Plans are underway to potentially expand this line of research on Ancestral Puebloan sites by visiting Chaco Canyon to perform sound studies using specialized equipment, including Class 2 sound level instruments compliant with ANSI S1.4/ IEC 61672-1 (IEC 2013) standards. Fieldwork will also include phenomenological and psychoacoustic aspects by recording people’s experience of sound in the field.
Chapter 8. Case Study 2: The Maya City of Copán

As discussed in Chapter 6, exploring archaeoacoustics within the ancient Maya city of Copán consisted of applying both the Soundshed Analysis Tool, and later creating and applying the Soundshed Analysis – Variable Cover Tool. This case study also overcame a limitation of the work in Chaco Canyon by utilizing a reconstructed Urban DEM as the basis for sound modeling. Located in Honduras, Copán was an important commercial and cultural center of the Classic Maya world from the fifth to ninth centuries CE. At its apogee, the city encompassed over 250 square kilometers (Goodwin et al. 2018b).

Maya Synesthesia in Iconography and Experience

For the Maya and many of the cultures in the Maya region synesthesia played a major role in human experience. Evidence of this “cross modality” is recorded through iconography, where visual signs indicate and suggest particular sensations, such as taste, smell, and hearing which ordinarily are not perceived through use of the eyes (Houston et al. 2006:136-7). In contrast to “taking it in,” an expression commonly heard today when describing sensual experience, the Classic Maya conceived of senses that were projected outward to experience the world. Sensory organs like eyes were believed to possess a form of agency and thus eyes were often illustrated with protruding optical stalks and eyeballs in Classic Maya art (Houston et al. 2006:167,178; Goodwin et al. 2018b).
“Speech scrolls” or “sound scrolls” were used in the iconography of Maya region as early as 500 BCE, as seen on Kaminaljuyu Stela 9 where a man standing atop the earth crocodile is depicted “playing” a conch trumpet (Houston et al. 2006:139). Though these visual representations of sound are most often referred to as speech scrolls, during the Middle and Late Formative periods (c. 900-100 BCE) their meaning and usage in the iconography of the region came to include and evoke sensations of smoke, mist, breath, sounds, speech, and echoes, among other phenomena, often simultaneously, and was not limited to issuance from human sources. For example, the mouth of a cave is depicted on a Middle Formative Olmec carving (Chalcatzingo Monument 1) as exuding speech scrolls, indicating clouds or mist emanating from within with a breath-like sound, and a Classic Maya ballcourt image shows echoes as speech scrolls projecting from the architecture (Houston et al. 2006:139, 163).

Iconography of aromatic flowers, beads, and precious stones, such as jade, are also intertwined with depictions of sound. This may have Middle-Late Formative Olmec origins, as in Olmec iconography, speech scrolls were used to indicate the sound-producing capabilities of jade belt celts (Houston et al. 2006:139). Verbal expression is depicted as a string of beads rather than a speech scroll on Lacanha Stela 1 (Early Classic Maya), and hearing is represented in Classic Maya art as flower shaped earspools with sound or breath volutes. “Sounds of beauty,” such as song, included bead and flower elements, as did iconography of courtly speech and hearing. This symbolism was also related to the breath soul and flower world tying sounds and scents together synesthetically with conceptions of the afterlife (Houston et al. 2006:154-6, 178). Maya
scripts were meant to be read aloud and speech and sound scrolls illustrate the importance of changing volume in vocal readings or performance (Goodwin et al. 2018b).

Evidence of the importance of music in the Maya world can be found in a variety of iconographic records. The Bonampak murals show trumpets and rattles being played amidst a battle, and images on polychrome vessels show shell horns, bark trumpets, and whistles being played by musicians and spectators at ball games (Katz and Stanton 2020:13,16-17). Miller describes the Classic Maya musical ensemble as a band – characterized by their ability to form a mobile procession as in the Bonampak murals (1988: 319). The Maya band also had a standardized “marching order”: first were rattles; then flutes, if present; followed by the large huehuetl drum; turtle shells played with antlers; teponaztli wooden drums; trumpeters playing bark, gourd, or shell trumpets; and occasionally a final rattle (Miller 1988:326-30 see also Houston et al. 2006:258). In addition, conch horns were often associated with hunting or hunting deities (such as Huk Siip, often depicted with a shell horn) and were given personal or deity’s names. Evidence suggests these marine shell trumpets were used for a variety of purposes, such as to startle or disorient prey animals, communicate and coordinate actions among hunters or fighters, or to announce arrivals or victories (Houston et al. 2006:264, Katz and Stanton 2020:14).

Performance, music, and dance in concert with Maya art and architecture was a means of bringing together the senses to structure experiences that communicated cultural information (Goodwin et al. 2018b; Houston et al. 2006). To explore the ancient Maya city of Copán synesthetically this case study fused modeling produced via the
Soundshed Analysis Tool and its variants, with Virtual Reality (VR) technology to investigate sights and sounds during the Classic period.

**Stelae, Architecture, and Ritual Performance at Copán**

From 427-820 CE, the Kingdom of Copán was presided over by a dynasty of 16 kings (Remondino et al. 2009:1). During this time, Copán’s rulers erected a number of monuments, structures and other ritual and architectural features, including a series of stelae documenting important events and ritual actions that were performed within a *k’atun* (20 year period), including royal ascensions and cycle endings, marriages, alliances, royal genealogy, and heir designations. Not only did these stelae hold ritual significance, but they also ordered the spatiotemporal environment within the main ceremonial complex (Newsome 2001: ix-xvi).

Considered to be one of Copán’s most important kings, Ruler 13 (*Waxaklajun Ub’aah K’awil*, or “18-Rabbit-God K”) reigned over kingdom from 695 CE until he was decapitated by a nearby vassal state in 738. Ruler 13 was responsible for transforming the city’s Great Plaza by enclosing it with bleachers and erecting seven stelae within, and was generally known for introducing high-relief stelae and sculpture to Copán (Goodwin et al. 2018b; Richards-Rissetto 2010). Newsome has argued that the seven stelae installed by Ruler 13 created a ritual circuit that he traversed in public performances “affecting the sensory and supernatural worlds (2001:154).”

Inscriptions on Ruler 13’s Stelae follow a formula. First, the stela is identified as a “holy object” and its dedication equated with a godlike action of ordering the cosmos.
Next, the chronology of the *k’atun* is described. Stela C begins the cycle, followed by Stela F to the east, Stela 4 to the west, Stela H to the southeast, Stela A in the southwest, Stela B to the north, and ending with Stela D in the northernmost location near the plaza stairs (Newsome 2001:154-5) (See Figure 8.1).

**Figure 8.1.** Illustration of Ruler 13’s Stelae Progression

Another achievement of Ruler 13 was the construction of Temple 22 (Structure 10L-22, dedicated in 715 CE, one *k’atun* after his ascension) in the East Court of the Acropolis. Although small, with an interior space measuring 25.5x11.5m, Temple 22
featured ornate external and internal sculpture and is believed to represent the ordered Maya universe as well as the sacred mountain of creation (von Schwerin 2011: 273-5). Copán’s Acropolis was the exclusive domain of the rulers and consisted of an elevated area located south of the Great Plaza where its architecture simultaneously possessed both conspicuous visibility and inaccessibility to the common people. With the court of the Acropolis rising at a minimum of 10-12 meters above the Great Plaza at its base, and the Acropolis architecture rising further still, the commanding height of the structures likely conveyed the message “that the ruler’s high position placed him closer to the heavens, making him the only person allowed to interact with supernatural ancestors (Richards-Rissetto 2010:13).”

Each of Copán’s rulers was responsible for the installation of new public works, often building upon previous architectural modifications. For example, twenty five years after Waxaklajun Ub’aah K’awil’s reign, Ruler 16 (Yax Pasaj Chan Yopaat) commissioned the addition of four new buildings within the Acropolis (Structures 10L-11, 10L-16, 10L-18, and 10L-22A) in addition to several monuments (Richards-Rissetto 2010:40-3) (See Figure 8.2). It is likely that these deliberate modifications to the built environment or “space,” also intentionally impacted ritual performance and, therefore, the experience of “place” within Copán.

The ancient Maya political and religious spheres both featured ritual circuits and processions that consisted of the performance of certain acts at stations along the circuit. Depending on the rite performed, the rate of movement between stations could vary, and
the acts performed there could take place over durations spanning from minutes to years. Using a combination of ethnographic, historic, and Classic Maya accounts, Reese-Taylor has defined three categories of ritual circuit: base-to-summit-of-mountain, periphery/center, and ritual circumambulation (2002:145).

In a base-to-summit-of-mountain circuit, the ritual actor ascended from one level to another, such as the procession of a Maya ruler up a temple staircase. This ritual was typically performed along a north-south axis and symbolizes the progression “from the
underworld through the human world and into the heavens (Reese-Taylor 2002:159-60). A periphery/center circuit, or banner procession, typically originated in a central location and involved the carrying of standards or ritual objects outward toward the periphery along cardinal directions in a counter-clockwise fashion. These rituals would take place between the urban core and outlying areas to strengthen ties with remote settlements, and often followed formal pedestrian paths or *sacbeob* (Reese-Taylor 2002:152-9).

A ritual circumambulation was performed to symbolically denote one’s domain. This circuit was typically completed in a counter-clockwise manner which corresponded to several cyclical periods: the rising and setting of the sun, the cycle of seasons, the cycle of life, and that of creation. Structures and monuments were often arranged to facilitate such movement linking architectural organization and “cosmic geography” (Reese-Taylor 2002:144, 146-9).

Given the constantly evolving arena of Maya performance space, this study posits two objectives. First, is to investigate the potential role of sound and sight in Ruler 13’s stelae circuit. Who could see or hear the performance as he walked from stelae to stelae? Were some people able to do both? What might the results tell us about Maya performance and its intended audience? The second objective is to explore temporal changes in Copán’s urban architecture. How did the atmosphere of performance spaces change when Copán’s final dynastic king, Ruler 16, commissioned new buildings in the Acropolis? How were the visibility and acoustics of ritual performance affected (Goodwin et al. 2018b)?
Methods of Investigation: Scenarios 1 and 2

These scenarios were explored using a three step approach: (1) creation of a simulated ancient landscape; (2) viewshed and soundshed modeling; and (3) a blending of estimated visual and sonic experiences via VR to advance towards a synesthetic approach. It is intuitive that working with a representation of the ancient landscape rather than modern data whenever possible provides greater modeling accuracy. This is especially true when performing viewshed or soundshed analyses in GIS, as both are tied directly to the available elevation data for the study region. However, creation of this data is time consuming, therefore, it is not universally available for all sites. For this research the reconstruction of the ancient landscape was provided by Heather Richards-Rissetto, director of the MayaArch3D Project and the MayaCityBuilder Project, in the form of “Urban Digital Elevation Models (DEMs)” (MayaArch3D 2020; MayaCityBuilder 2020).

Urban DEMs that simulate the ancient landscape of Copán were created using a combination of modern LiDAR, GIS, and 3D modeling. Their creation originated by digitizing maps prepared by the PAC I (Proyecto Arqueológico Copán, Phase I) settlement survey in the 1970’s, collecting UTM coordinates for the survey’s site grid in the field via GPS, and georeferencing the digitized maps (Richards-Rissetto 2010:170-1). The process of digitizing and georeferencing maps continued for additional sources based on surveys completed after PAC I, after which Richards-Rissetto meticulously created vector data by tracing structures and other features by hand in GIS (2010:176). These line files were converted to polygons, assigned attributes, including structure elevations which were derived from architectural drawings, excavation data, and
trigonometric functions, and ultimately the resulting data was converted into raster format or “Urban DEMs” (Richards-Rissetto 2010:178-189, 190-195).

The Urban DEMs were subsequently updated for modeling accuracy using multi-sensor/multi-resolution photogrammetry featuring terrestrial and aerial image collection (Agugiaro et al. 2011; Remondino et al. 2009), 3D modeling using SketchUP and 3D Studio Max (Goodwin and Richards-Rissetto 2017; Lyons 2016; Richards-Rissetto 2010, 2013; Richards-Rissetto and Plessing 2015; von Schwerin 2011) and airborne LiDAR commissioned for the MayaArch3D Project in 2013 (von Schwerin et al. 2016). As a result, 0.5 m resolution DEM (reflecting modern conditions) and DTM data were available for 25 km² surrounding Copán’s main civic-ceremonial complex. The DTM data was then incorporated into the Urban DEMs which combined the bare earth terrain elevations (without vegetation) with Copán’s mid to late eighth-century structure heights.

Viewshed and Soundshed modeling for scenarios 1 and 2 were both completed using the Soundshed Analysis Tool v.0.9.2. As urban areas, neither Copán’s Great Plaza nor the Acropolis featured dense vegetation which would have resulted in additional attenuation of sound, thus requiring the use of a different modeling tool. For the first scenario, estimated soundsheds of the Great Plaza stelae circuit were produced by utilizing a person’s raised voice as the sound source and modeling the spread of sound

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36 Note that for this case study, the full suite of modeling parameters are specified within the legend of each resultant figure.
from speaker locations at each of the seven stelae and at the top of Structure 10L-4 which was also commissioned by Ruler 13 (See Appendix F for complete modeling results).

Figure 8.3 shows the maximum extent at which Ruler 13 would be audible as he completed the stelae circuit. Listeners would need to be located within the indicated areas to hear his speech\textsuperscript{37}, however, not all vantage points afforded listeners the opportunity to

\textsuperscript{37} As described in Chapters 4 and 7, audibility does not denote speech intelligibility, which was not analyzed for this case study.
hear Ruler 13 through the entire stelae circuit. For example, Figure 8.4 shows the estimated soundshed of Ruler 13 speaking from Stela C, the first location in the stelae circuit. Here anyone observing from the stairs to the north, west, or east of the stela would be able to hear his voice. Comparing the soundsheds for each of the stela (see Appendix E, Figures E-1.1 to E-1.8), the optimal locations for listening to Ruler 13 would have included portions of the northern staircase, especially those areas closest to Stela D, and the southern half of the eastern staircase (see Figure 8.5). Comparing the viewsheds for
Figure 8.5. Optimal Locations for listening to Ruler 13 from the Great Plaza Stairs

Each of the stela (see Appendix E, Figures E-3.1 to E-3.8), the optimal locations for viewing Ruler 13 during his circuit would have paralleled the audible areas with some portions of reduced visibility. Here the southern half of the eastern staircase would have provided the best view, although portions of the northern staircase still afforded high visibility (see Figure 8.6).

For the second scenario, changes to the viewsheds and soundsheds within the Acropolis were compared for two time periods in order to investigate the impact of Ruler 16’s massive building campaign on sight and sound in the city (Goodwin et al. 2018b).
This scenario was investigated by modeling the sound of a conch shell horn being played at 13 points along a proposed procession route. The circumambulation route traced a counterclockwise path from the West Court to the East court of the Acropolis, as was common in ancient Maya ritual performance (Baudez 1991; Reese-Taylor 2002:146; von Schwerin 2011:290-1), and modeling was completed using two Urban DEMs representative of extant structure heights during the reigns of Rulers 13 and 16 (See Appendix E for complete modeling results).
As seen in Figure 8.7 the maximum extent at which the shell horn would be audible if played in the Acropolis procession during the reign of Ruler 13 includes much of Copán’s urban core within a radius of approximately 500m from the sound source location while travelling along its route. Those in the eastern part of the city would have been excluded from hearing the procession, while those in the Great Plaza, the elite complex to the north, and the elite suburb of El Bosque to the west, as well as hilltop areas to the Southeast would have been “part” of this experience (Goodwin et al. 2018b).
Figure 8.8. Estimated Soundshed of a Shell Horn played from the East Court (Point 11) at an Acropolis Procession during the reign of Ruler 13.

Like the stelae circuit, architectural variability within the Acropolis resulted in differing propagation patterns from each waypoint along the procession. For example, when the conch is played from the center of the East Court (Point 11) sound escaping the court propagates to the Southeast and Northwest (See Figure 8.8). As the procession continues to begin ascending the East Court’s Jaguar stairway (Point 12), sound
Figure 8.9. Estimated Soundshed of a Shell Horn played from midway up the East Court’s Jaguar Stairway (Point 12) at an Acropolis Procession during the reign of Ruler 13

propagates directly to the North and South, including different audiences along the way (See Figure 8.9).

As described in Chapter 4, one of the primary differences between visibility and audibility is the level of participation required by the observer. A conch played along the Acropolis procession route would still be passively audible beyond the Acropolis itself, a
location inaccessible to the majority of observers. Thus the exclusiveness of the procession could be simultaneously reinforced while the occurrence of the ritual acts would be known to all those within the soundshed extent who understood the meaning of the horn’s call. This is further illustrated by Figure 8.10 in which the viewshed of the shell horn being played from the center of the East Court (Point 11) has been superimposed on the estimated soundshed for that location. Only those within the blue areas, primarily confined to the East Court, could see the musician.

**Figure 8.10. Visibility of a Shell Horn Player within the East Court (Point 11) at an Acropolis Procession during the reign of Ruler 13**
Referring back to Figure 8.2, Ruler 16’s modifications to the architecture of the Acropolis can be seen. As expected, the resulting impact of these changes to the Acropolis procession’s maximum soundshed extent is a reduction in audible area (see Figure 8.11), particularly group 9L-16 to the northeast of the Great Plaza, and parts of group 10L-18 in the suburb of El Bosque.

**Figure 8.11.** Comparison of Maximum Soundshed Extents of Shell Horns played at Acropolis Processions during the reigns of Ruler 13 and Ruler 16
Figure 8.12. Comparison of the Estimated Soundshed Extents of Shell Horns played atop the Jaguar Dance Platform (Point 13) in the Acropolis Processions during the reigns of Ruler 13 and Ruler 16

Variation along individual procession waypoints also occurred over time. These ranged from minimal changes for central procession waypoints, where the changes in architecture had little effect, to much more dramatic results (see Appendix E, Figures E-11.1 to E-11.13). For instance, at the final location in the procession atop the Jaguar dance platform (Point 13), the audibility of the conch decreased significantly between the
reigns of Rulers 13 and 16\textsuperscript{38}. Figure 8.12 illustrates this reduction of approximately 25%: from an area of approximately 209,655 \text{m}^2 during the Ruler 13’s reign (area enclosed by red polygons), to 157,709 \text{m}^2 following Ruler 16’s building campaign (area enclosed by yellow polygons with SPL indicated). The reduction in audibility was accompanied by an

\textbf{Figure 8.13}. Visibility of a Shell Horn player atop the Jaguar Dance platform (Point 13) at an Acropolis Procession during the reign of Ruler 13

\textsuperscript{38} See Appendix E, Figures E-4.13 and E-7.13 for individual soundsheds at Point 13 during the reigns of Rulers 13 and 16 respectively.
even more dramatic reduction in visibility, excluding much more of El Bosque from seeing the conch player on top of the Jaguar dance platform during Ruler 16’s time (compare visible areas represented by blue polygons in Figures 8.13 and 8.14).

Figure 8.14. Visibility of a Shell Horn Player atop the Jaguar Dance Platform (Point 13) at an Acropolis Procession during the reign of Ruler 16.

The final portion of this case study featured a VR exploration of estimated visual and sonic experiences during the stelae circuit and Acropolis procession based on modeling results produced by the Soundshed Analysis Tool. VR walkthroughs were
created by Graham Goodwin and Heather Richards-Rissetto using the gaming engine Unity, the Oculus Rift headset, and DearVR (a unity plugin that simulates spatial sound) (Goodwin et al. 2018b). VR allows researchers a way to access the experiential realm as enhanced by interactions of our visual and auditory systems. This is of primary importance in places like Copán where today’s landscape is not representative of the ancient built environment. In addition, VR reconstruction presents an opportunity for researchers like myself, who have never travelled to Copán, some measure of remote access to the site and the activities that occurred there.

**Subject-centered VR Narrative: Scenario 2**

Experiencing the Acropolis procession from the viewpoint of a participant while a musician plays the conch from the Jaguar dance platform during the reign of Ruler 16, the first thought that comes to mind is how tall and commanding the surrounding architecture is.

As I enter the West Court, my view of the Acropolis is temporarily obscured by the Acropolis platform, rising to my left. I turn towards it while I walk, and I’m tempted to look up at it, his majesty Yax Pasaj’s new building [Structure 10L-11] is up there, but that’s not what I came for, my role is to carry this standard for the ruler (Reese-Taylor 2002:152-9). Besides, I can see his new addition at the top of Temple 16 [Structure 10L-16] up ahead. Like most of the architecture here, it’s elevated far above me, has to be 30 meters up, and it’s enclosed so I can’t peek in. I turn right (south) past several altars and monuments, then east where the sound of the horn player is almost completely muffled by the imposing architecture creating a tunnel-like entrance into the East Court and giving me a
momentary feeling of isolation. Straight ahead I can see another new building [Structure 10L-18], they’re literally everywhere I turn. I hope this is a good sign that his majesty can speak to the gods on our behalf, the soils have become less productive even though the population has continued to grow (Richards-Rissetto 2010:73; Webster 2005:42-4). As I turn left (north) and follow the procession through the East Court the sound of the conch grows louder, resounding into the larger open space. As I begin to climb the Jaguar stairway, my view opens up and I feel less enclosed. I can see so much more and I feel the sound of the conch spreading outward above the Acropolis architecture to the people beyond – I turn back towards the interior of the court, but I wonder if the people beyond the Acropolis can see me too?

“Experiencing” the Acropolis procession through VR there is a noticeable dichotomy between movement through the interior of the Acropolis courts, surrounded by “intimidating” architectural features, and the sights and sounds associated with ascending the stairway. Although the courts are open air spaces, there is a distinct “feeling” of enclosure or isolation which aligns with the exclusiveness of events that would have taken place there. This is in sharp contrast to the final location upon the Jaguar dance platform where there is an explicit sense of height and spectacle. Throughout the procession, thoughts and feelings are dominated, and perhaps intentionally directed, by the built environment as experienced through the senses of hearing and vision.
Summary and Further Work

While both scenarios 1 and 2 investigated forms of ritual circumambulation, the stela circuit and Acropolis procession represent two very different types of public performance. Located within the Great Plaza, rituals performed during the stela circuit would have been accessible to all. The surrounding staircases offered bleacher-like “seats” from which to see or hear Ruler 13 first hand, and *sacbeob* leading into the Plaza from the east and west would have channeled the movement of people to the Plaza. Given that the Stelae included texts meant to solidify Ruler 13’s position, equating his rule with the divine ordering of the cosmos and recording important events over the course of his reign (Newsome 2001), it is not surprising that the monuments were constructed in such a conspicuous public arena, nor that the Ruler would be visible and audible from almost any position on the surrounding staircase.

In contrast, the soundsheds, viewsheds, and VR walkthrough of the Acropolis procession all reinforce the restricted, exclusive nature of the Ruler’s circumambulation. Only some select elite were allowed to participate in the Acropolis procession, the ritual circumambulation reinforcing the Acropolis as the ruler’s domain. The exclusive nature of this performance may have reflected the Maya notion that to “see” or “overlook” was associated with higher status, and to enforce the idea that to be all-seeing (from the Ruler’s high vantage point) was to be all-knowing (Goodwin et al. 2018b; Houston et al. 2006:167).
For these modeling scenarios where activities took place within anthropogenic urban environments, the Soundshed Analysis Tool proved sufficient, however, outside of Copán’s urban core a different modeling tool was required to account for areas of ecological variation.

*Kahkab and Ritual Practice in Suburban Copán*

The ancient Maya concept of *kahkab*, a combination of *kah* (earth) and *kab* (community) implies that even in cities, both built and natural features were important components of the landscape (Marcus 2000; Richards-Rissetto et al. n.d.) In the Late Classic period (c.600-822 CE) the Copán Valley population expanded from about 6,400 people in 675 CE to 20,000-22,000 people by 900 CE causing growth in the foothill zones surrounding the city (Richards-Rissetto 2010:40; Webster 2005:42-4). Beyond Copán’s Principal Group the *sacbeob* give way to informal paths leading to suburbs where patches of maize, beans, and squash were grown amongst extant vegetation, and deforestation occurred to support hillside Maize cultivation (Fedick 1996; Ford and Nigh 2009; Graham 2008; Killion 1992; Webster 2005:42-4).

As described previously, Maya ritual processions and performance of rites were not confined to particular locations – in this case, Copán’s urban core. Performances within outlying settlements could strengthen ties with the core, bolster the Ruler’s claim to those areas, and achieve other sociopolitical objectives (Reese-Taylor 2002). To these ends, Ruler 12 (Smoke Imix) erected seven stelae within the valley surrounding Copán among these were Stela 10, located approximately 3.2km west of the urban core, and
Stela 12, located 1.2km to the southeast (see Figure 8.15) (Fash 1983; Richards-Rissetto 2010:41).

**Figure 8.15.** Location of Stelae 10 and 12, Copán, Honduras

Stela 12 was erected by Ruler 12 in a low-density outlying settlement to celebrate the 9.11.0.0.0 period ending on Oct. 9, 652 CE (Morley 1920:132-6; Richards-Rissetto et al. n.d.). Originally painted red, Stela 12 measured 3.25m tall, 61cm wide, and 52 cm deep and was situated on an 8m x 5m leveled terrace (Morley 1920:132). According to Richards-Rissetto et al.(n.d.), “several hypotheses exist about Stela 12’s significance: (1)
it was a sun marker, along with Stela 10 that identified the onset of planting season (Morley 1920), (2) it formed part of a line-of-sight communication system for relaying smoke signals (Fash 2001), (3) it served as a territorial marker for the Copán polity (Fash 1983, 2001), (4) it was a locus for ritual and community events, and (5) it served as a destination for ritual processions (Carter 2010; Richards-Rissetto 2010).” Given the remote location of Stela 12 in Copán’s hinterlands, the objective of this study is not to interrogate each of these hypotheses, but rather begin to gather new multi-sensory data to further the understanding of ancient Maya ritual processions.

**Methods of Investigation: Scenario 3**

Like Scenarios 1 and 2, Scenario 3 involved the investigation of ritual performance at Stela 12 through a tripartite approach: (1) utilization of a simulated ancient landscape; (2) viewshed and soundshed modeling; and (3) a blending of estimated visual and sonic experiences via VR. As described in Chapter 6, the Soundshed Analysis – Variable Cover tool was created to explore the effects of vegetation attenuation or variable ground cover types on audibility. To explore the roles of sight, sound, and movement in Scenario 3, modeling was completed using both the original Soundshed Analysis Tool, and the Variable Cover tool.

The objectives of multiple modeling options were to (1) further develop the Soundshed Analysis Toolbox to account for additional ecological variability (in this case: urban gardens or orchards, maize fields, forests, etc.), (2) analyze the impact of vegetation within urban agrarian landscapes on viewsheds and soundsheds, and (3)
explore the cultural significance of Stela 12 using a multi-sensory approach, and more generally the role of synesthetic experience in ancient Maya society (Houston et al. 2006; Richards-Rissetto et al. n.d.).

Vegetation Reconstruction and Modeling

In the 1980s Copán’s vegetation was classified according to five physiographic zones, low terrace, intermountain pocket, high terrace, foothills, and floodplain (Baudez et al. 1983). These zones, as well as waterbodies and urban areas, seen in Figure 8.16, were mapped in GIS by Heather Richards-Rissetto in 2008 and supplemented by data from multiple sources (House 2007; McNeil 2009, 2012; Richards-Rissetto 2010:45-54; Richards-Rissetto et al. 2016). Palynological data from pond sediment cores provided plant species classifications with associated AMS dates (McNeil et al. 2010) and these were used to identify which species were present during specific time periods (e.g., Preclassic, Early Classic, and Late Classic) for landscape simulation purposes.

As described in Chapter 6, the Soundshed Analysis - Variable Cover tool currently models attenuation based on four general categories of vegetation. For this analysis the seven physiographic zones within the Copán study area were divided into vegetation attenuation categories as follows: Category A included water, urban areas, low terrace, intermountain pocket, and high terrace; and Category B included foothills, and floodplains. No category C or D areas were modeled based on the data resolution.
To analyze the impact of vegetation to sight and sound, both the Soundshed Analysis Tool and the Variable Cover tool were provided the same environmental input values, including the use of a single ambient Sound Pressure Level of 31 dBA. The models assume the conch shell trumpet is being played on a warm, humid day (26° C, 90% humidity) during the wet season (May-November) in the early morning. Therefore, the only difference between the models is that the Variable Cover tool includes formulae
to calculate vegetation attenuation based on the categories assigned to the physiographic zones (Compare Figures 8.17 and 8.18\textsuperscript{39}).

**Figure 8.17.** Soundshed Analysis Tool modeling inputs for Copán Scenario 3

\textsuperscript{39} Note that these figures show an earlier version of the GUIs for the respective tools.
Stela 12 and its modeled soundsheds are located entirely within the foothills physiographic zone. The presence of vegetation in the area surrounding Stela 12 results in degree of sound attenuation that would have ranged between the two estimated soundsheds created by the soundshed tools, therefore, the experience of the listener should interpreted as a reality somewhere between these extremes. The estimated soundshed created with the Soundshed Analysis tool (see Figure 8.19) which
Figure 8.19. Estimated Soundshed of a Shell Horn played at Stela 12 Created using the Soundshed Analysis Tool

encompasses a larger and more multi-directional area illustrates how far the conch could be heard without intervening vegetation to muffle its sound (i.e., no vegetation attenuation). The soundshed created with the Variable Cover tool (see Figure 8.20) presents a much more conservative auditory experience showing the impact of thicker vegetation in this area (i.e., with vegetation attenuation). Taking these results together, we can determine that those in the immediate vicinity of the conch, as well as those...
Figure 8.20. Estimated Soundshed of a Shell Horn played at Stela 12 Created using the Soundshed Analysis – Variable Cover tool

located to the north and northeast of the sound would have heard the instrument being played regardless of whether the vegetation was low, or taller and thicker, up to the thickness of dense shrubbery. The audibility of the conch to those in the south and southwest would likely have been impacted by the intervening vegetation.
VR Integration

As with scenarios 1 and 2, scenario 3 Graham Goodwin and Heather Richards-Rissetto incorporated the results of soundshed modeling in their creation of VR simulations of the soundshed and viewshed of a person walking the hillside near Stela 12 as a shell horn is being played. VR simulation also included the use of sounds captured in the field along with reproduced sound sources such as a conch shell, whistles, and flutes (Goodwin 2018; Katz 2017; Richards-Rissetto et al. n.d.). Through use of the DearVR plugin, auditory effects such as occlusion, obstruction, and distance correction are included in the walkthrough to provide a realistic sense of one’s position relative to the sound. The result is simulated sound waves are partially blocked, reverberation occurs, and perceptions of loudness and distance are altered (Richards-Rissetto et al. n.d.). A VR walkthrough can be viewed online at: https://www.youtube.com/watch?v=qHUnxNn4C3g&feature=youtu.be. Vegetation appearing in the VR environment comprise initial simulations using a range of temperate and tropical plants rendered in the gaming engine Unity using GIS footprints (Day and Richards-Rissetto 2016; Richards-Rissetto et al. n.d.).

Discussion and Future Directions

Rituals performed at Stela 12 most likely represented a periphery/center circuit, or banner procession, meant to strengthen ties between the urban core and the hillside maize production communities (Reese-Taylor 2002:152-9; Webster 2005). The landscape between these locations featured natural vegetation, deforested areas, maize
and crop production, and settlements with urban gardens, all interspersed between architecture and monuments connected by informal trodden paths. As seen in the preliminary modeling results, these vegetation and land cover features impacted the audibility and visibility of political and ritual events taking place within and outside Copán’s urban core – events intended to be observed by an audience. By incorporating GIS audibility and visibility modeling into VR simulations grounded in archaeological evidence, researchers are provided with a manner of sensory engagement with the past, allowing further exploration of hypothesis about impacts to, or because of, performances.

Although Baudez et al.’s physiographic zones (1983) provided an established baseline for vegetation reconstruction at Copán, it is clear that further refinement of the landscape reconstruction will be necessary to achieve the most accurate modeling results. Work is ongoing to add Category C and D vegetation to a high resolution (1m) land cover reconstruction raster, capturing the irregular nature of ecological micro-variability within the physiographic zones. Soundshed modeling at Copán will continue as new data becomes available (Richards-Rissetto et al. n.d.).
Chapter 9. Case Study 3: Irish Reinterpretation of the Landscape

The third case study presents a departure from the previous studies in several ways. This study explores the reuse and reinterpretation of Early Medieval Irish domestic sites in the physical and religious landscape of late nineteenth- and early twentieth-century Ireland. Focusing on seven cillíní (children’s burial grounds) located just outside the town of Headford, in County Galway, Ireland, it not only represents a study in the historic period, but focuses on quotidian rather than monumental landscapes. Although grounded in ritual activity, and thus possessing elements of ritual performance, what was not heard or how sounds were contained is arguably more important than the spread of sound in this context. In addition, as discussed in Chapters 3 and 4 ethnographic materials and personal narratives provide added context for interpreting the historic soundscapes through the emic perspective, moving beyond a reliance upon only the phenomenological descriptions of “disengaged” archaeologists. Even so, those sharing a twentieth-century context for mourning and remembrance may have little left to critique of a phenomenological approach of exploring the relationship between these important sites and sound. Cillíní continue to be powerful reminders of personal and familial history today, as they were in the past.

From Raths to Cillíní: Site Formation and Use, Site Reinterpretation and Reuse

As in the previous two case studies, the landscape surrounding the Town of Headford in County Galway has been inhabited for millennia as evidenced by the great number and variety of sites dating from the Neolithic to the Early Modern period. Among
these are 25 listed by Ireland’s Record of Monuments and Places (National Monuments Service 2017) as “raths” or “ringforts.” Raths were Medieval Irish enclosed homesteads that were typically situated on slightly elevated terrain (e.g., drumlins) overlooking fertile farmland (Edwards 2005:238-9). Raths were typically univallate (i.e., enclosed by a single bank) circular or ovate earthen structures with an average diameter of 30 meters constructed via excavating materials from a bounding ditch surrounding the bank or banks. Wooden fences topped the berm, completing the enclosure. Raths were entered through a gated causeway and entrance passage crossing the ditch and berm, typically oriented towards the East. Bivallate and trivallate forms also existed, and a small number of raths also featured anthropogenically modified raised central interiors (Edwards 2005:239-44; O'Sullivan and Nicholl 2011:63-5).

During the Early Medieval period (sixth to ninth centuries CE) the raths contained circular houses approximately 4.7 to 7 meters in diameter constructed from inner and outer wattle walls filled with insulating materials (e.g., straw, moss, etc.) (Edwards 2005:244-8; O'Sullivan and Nicholl 2011:60-1). Inhabitants of the rath could include men, women, and children various socioeconomic status as defined in early Irish laws (e.g., lords, commoners with and without their own holdings, semi-free tenant classes, and slaves) as well as itinerant specialists (e.g., coppersmiths, specialist tradesmen).

40 Although the term “ringfort” has also been used throughout Ireland, this chapter refers to these features as “raths” to avoid the misconception that they functioned as fortifications. Historically, the term ráth referred to “a ringfort with one or more enclosing earth banks” while lios referenced “the enclosed space within” (Edwards 2005:239). These terms, and others, have been preserved in some place names (see Edwards 2005:239 for additional examples).
Outbuildings, formal pathways and livestock also occupied the rath and documentary evidence indicates that trespass of another household’s enclosure was against the law. This has been interpreted to show that membership within the household as defined by the boundaries of the rath made up an important part of Medieval Irish identity. Even during the earliest occupation of raths there was a sense that the enclosed lands were distinct from the surrounding landscape (O’Sullivan and Nicholl 2011:61-7).

By the tenth century, raths were no longer the preferred settlement sites, and while some continued to be occupied, no new raths appear to have been constructed. As rectilinear house forms were introduced, settlements shifted towards open areas of the landscape. This settlement shift is also coincident with socioeconomic changes: years of hierarchical laws resulted in the emergence of powerful elite dynasties and a decreasing number of free or landed people (Edwards 2005:298-300).

During the fifth century, Christianity had reached Ireland, spreading from both Britain and Gaul (Hughes 2005a:301). By the ninth century, churches, like raths, dotted the landscape and Christian religion had become part of Irish culture. Along with the tenants of faith, the church brought socioeconomic impacts, becoming a center for education and skilled craftsmanship and contributing to the shape of law (Hughes 2005b:635). One such influence of the Roman Catholic tradition was the exclusion of various categories of individuals from burial within consecrated grounds, including those with differing religious beliefs, suicides, murderers and their victims, and sometimes the mentally ill or casualties of contagious diseases (Dennehy 2016:213; Finlay 2000:408-9; Murphy 2011:409). Among those excluded from churchyard burials were stillbirths, and
other unbaptized infants or children who’s souls were to spend eternity in “limbo”. These infants and children were laid to rest in *cillíní*, separate children’s burial grounds. While use of *cillíní* originated between 500-1600 CE, they appear directly in historical accounts beginning in the seventeenth century (Dennehy 2016:217-8; Finlay 2000:408-9; Murphy 2011:409-10).

The placement of *cillíní* in marginal areas of the landscape, paralleled the liminal status of the burial grounds’ inhabitants. While some argue that this was done consciously (Dennehy 2016; Finlay 2000) others suggest that these locations were simply less likely to be physically disturbed. Murphy writes, “The use of an ecclesiastical enclosure, a ring fort [a rath] or any archaeological monument on the landscape would have afforded the *cillín* with physical protection since it would be clearly marked and known on the landscape (Murphy 2011:417).” *Cillíní* were located along townland and field boundaries, or were placed in previously abandoned raths, ecclesiastical areas, or other reused monuments. Regardless of the location, they tended to be secluded areas separated from any contemporaneous use of active sites, such as the placement of a *cillín* outside a church enclosure (Finlay 2000:409-11; Lindow 2018:42; Murphy 2011:409).

Like many monuments and landscape features, raths and *cillíní* were systematically mapped by Ordnance Survey of Ireland surveyors in the early 1800s. Approximately 1400 children’s burial grounds are listed in Ireland’s Record of Monuments and Places, many of which are concentrated in the west of the country, however, due to the secretive use of *cillíní*, many more may be undocumented (Dennehy 2016:217-9). Evidence for past usage of these sites can be found in place names, oral tradition, and
historical records when grave markers were not use or are no longer extant (Edwards 2005:239; Finlay 2000:409-11; Primeau et al. n.d.:1). Archaeological evidence also indicates that infants were given individual wooden coffins or stone lined graves, similar to those buried via consecrated rituals. Wooden stakes, iron crosses, or white quartz pebbles would be used to mark graves as “passive memorials” emphasizing anonymity (Murphy 2011:420, 422-3). Historical and contemporary descriptions of cillíní burials suggest that these were performed at night, by the father of the deceased infant or another male relative (Garattini 2007; Murphy 2011; O’Sullivan and Sheehan 1996; Sugrue 1993). While the locations of cillíní were often known to immediate family members and were places for mourning and remembrance (e.g., Murphy 2011:416), this was not always the case, and sometimes mothers and other family members were not told where an infant was interred (Brennan 2012).

During the Second Vatican Council (1962-1965) Canon Law 1239 regarding child-limbo was relaxed by the Catholic Church and use of cillíní declined, however, Dennehy (2016:219) relates the use of a cillín as late as 1984 (Dennehy2016:218-9; Murphy 2011:411). Generations of such practices undoubtedly caused psychological trauma in addition to the grief of child loss or miscarriage, effecting many members of the deceased’s family (e.g., Brennan 2012; Murphy 2011). Shaffer Foster reminds us that “these are not just sites of archaeological significance, but part of an active landscape of mourning and remembrance for contemporary Irish people, who still visit these graves and pay tribute to deceased children, siblings, and other family members (Primeau et al. n.d.:4).
**Cillíní in the Irish Cultural Landscape and Ethnographic Record**

Following both the anthropological approach described by Howes discussed in Chapter 3 and the ISO understanding of “soundscapes” as discussed further below, it is important to place sensory characteristics surrounding the use of cillíní, site avoidance, and mourning/remembrance in their own cultural context (Howes 2008:445; ISO 2014:2). As such, this case study directly benefits from a project undertaken by the Irish Folklore Commission in the late 1930s, which grants an understanding of how the Irish cultural and religious landscape was experienced. The National Folklore Collection (NFC) includes both the “Main Manuscript Collection”, over 700,000 pages of material recorded in both English and Irish on 14 subject areas of oral history and folklore, and the “Schools’ Collection” consisting of over 451,000 pages of material on six topics provided by over 50,000 students within the Irish Free State who took part in the project (NFC 2021). These manuscripts yielded a rich ethnographic record of Ireland during British colonial rule and in its fledgling years of increasing independence (Primeau et al. n.d.:6). Recording these stories was part of “the quintessential practice of building places” (Valk

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42 Topic areas of the Schools’ Collection are listed as: “oral history, topographical information, folktales and legends, riddles and proverbs, games and pastimes, and trades and crafts” (NFC 2021).
and Sävborg 2018) and served to preserve folklore related to these locations in Irish cultural memory.

Schools’ Collection accounts reveal that Children’s Burial Grounds were still in use during the 1930s. One interviewee noted:

“There is a burial ground... [in] which unbaptised children are buried.... It is still used, but it is very few children that are buried there now a days because they do not die without Baptism. Still born children are buried there” (Fives n.d.).

The ethnographic record shows that by the nineteenth century, if not earlier, folk tradition led to the protection and preservation of raths and cillíní through systematic avoidance. As liminal places, raths were considered homes to fairies and for the modern Irish the terms “sidhe” and “sí” are used interchangeably to describe the fairies themselves or “fairy forts” (i.e., raths). In some cases fear of reprisal from the fairies still dictates people’s attitudes and actions regarding the position of sidhe in the landscape (Tilleson 2010). People also avoided disturbing or walking over known cillíní, which could result in consequences to their health. Dennehy writes: “These stories of contagion brought on by an unbaptized child’s grave may have been used to ensure the avoidance of a cillín as much out of fear as out of a desire to protect” (Dennehy 2016).

Schools’ Collection manuscripts also confirm that cillíní were to be avoided and left unaltered: one student recounts that “the people plough the land around it and they
don't touch that....” (McHale n.d.). Various accounts suggest that supernatural activity was associated with these sites:

“There was a flax mill in this field and every morning when the workmen went to work in it they used to see the tracks of little feet in the mill. They thought these were made by the children who had been buried in the fort” (Feeney 1939).

These accounts, written from an *emic* perspective, informed a culturally and temporally specific understanding of the Irish landscape, permit the interpretation of the auditory experience through an anthropological framework. Schools’ Collection narratives indicate that in the early twentieth century the location of *cillíní* were known; some *cillíní* were still in use; that the sites were afforded deference and were to be avoided; and provide evidence that due to traditional folklore and oral history many *cillíní* have survived to the present (Primeau et al. n.d.:5-6).

**The Acoustic Environment of Headford, County Galway**

During the period investigated by this case study, much of the land within Headford as well as lands in counties Roscommon, Limerick, Laois, and other areas of Galway were part of the estate owned by the (Protestant) Anglo-Irish St. George family (NUI 2011). In contrast with the St. Georges, the vast majority of Irish tenants who lived there and farmed their lands were Catholic. The St. Georges constructed a Protestant (Church of Ireland) church and parsonage in Headford, ordering the landscape differently than would the native Irish. Shaffer Foster notes, that “as landlords, the St. Georges appear to
have had a somewhat conflicted relationship with their tenants; an interviewee for the Schools Collection called one St. George landlord “old and cruel” (Egan 1937; Primeau et al. n.d: 15)."

The ISO defines acoustical environments as “sound at the receiver from all sound sources as modified by the environment” and defines "soundscape" as “acoustic environment as perceived or experienced and/or understood by a person or people, in context” (ISO 2014:2). It is, therefore, social context which makes sound such an important aspect of the placement and usage of cillíní in the landscape. People actively interacted with and interpreted soundscapes, deriving meaning from both what was heard, and what was not heard. The Headford of the St. Georges was one of English colonialism and contestation, yet it coexisted with a traditional Irish landscape. The sacred soundscapes associated with the Protestant churches reflected the political nature of English colonization. Although meaningful to the Catholic Irish tenants, these sounds were not necessarily welcomed during their own use of the landscape, including burials at cillíní (Primeau et al. n.d.:6-7).

The acoustic environment of a religious soundscape features high SPL sounds such as the ringing of church bells as well as low SPL quiet spaces. These are perceived as dominant sounds unable to be ignored, and meaningfully quiet sounds of worship (Mlekuz 2004; Williams 2013). Quiet, in both its definitions as antonyms of “loud” and “busy,” was used intentionally during services, singing, and in ritual contexts such as monasteries and cillíní (Williams 2013). Williams notes the similarity between musical and quiet spaces as “...similar qualitative types in that both require a relative lack of external
sound to function as desired by their users” (Williams 2013:196). The soundscape of reverent silence observable at the scale of structures or sites contrasts with that of the landscape scale, where the ringing of church bells not only signified the occurrence of important events but contributed to the intentional structuring of temporality and the maintenance of identity as a community (Mileson 2018; Mlekuz 2004). As stated by Mlekuz in the context of a Medieval Slovenian study, the sound of church bells could also “be understood in terms of Christianisation of wild, pagan, untamed and potentially dangerous landscapes, which symbolically opened the door for” and “structured the process of colonization” (Mlekuz 2004: Section 4.1).

Anti-Catholic Penal Laws were introduced from 1695-1728 in response to Irish Catholic uprisings and the Williamite War. These laws restricted land ownership, and subjugated Catholic religious practice, going so far as to ban church steeples and church bells (Donnelly 2004; Walker 2000). By 1705 Protestant Irish owned 85% of the lands, growing to 95% ownership by the end of the century. Catholic religious beliefs and practices were regarded as not reflective of “true” Christianity by the ruling class of Protestants, and priests turned to open-air “mass rocks” as places of worship (Donnelly 2004; Walker 2000). Thus, for some time, the ringing of church bells for the Catholic Irish did not necessarily signify an ordered call to worship, but may have well been the sound

43 Bell towers were also visually commanding, reaching vertically to the heavens and symbolizing a connection with God (Lindow 2018).
of oppression, “a violent imposition of colonial order,” similar to the situation described by Nickleson (2016) for colonial Canada.

Given the use of *cillíní* as places of secrecy, mourning, and remembrance in a colonial landscape, this study posits two objectives. First, is to investigate the liminal placement of *cillíní* through modeling estimated soundsheds. Could rituals of burial and mourning be heard within the greater landscape? Is there evidence that the spread of sound may have been managed or contained? The second objective is to explore the impact of colonial religious practices on traditional Irish Catholicism and in particular, use of *cillíní*. How did the acoustics of the Protestant faith manifest in the greater landscape? Is there evidence that *cillíní* were placed in locations where the acoustic envelope remained traditional or politically neutral?

**Methods of Investigation: Scenarios 1 and 2**

To investigate these questions, site location data for the 18 townlands that intersect the Study Area was gathered from the National Monuments Service. Redundant records, entries without associated coordinates, and records with descriptions/determinations stating that they were “not archaeological monuments” were removed from consideration. Of the 71 sites mapped, 38 were inset from the Study Area boundary by an arbitrary minimum distance of 150 m (Figure 1) to assure the production of a soundshed raster extending 360° around the sites. Presumed or confirmed *cillíní* were chosen from among this subset. Elevation data available for the study area consisted of a one meter resolution Digital Surface Model (DSM) obtained through
Bluesky Mapshop Ireland (2018). Unlike LiDAR data or Digital Terrain Models (i.e., “bare-earth” Digital Elevation Models), DSM data includes the elevations of reflective surface features such as buildings, walls, and trees. In this study, these features played a prominent role in the anthropogenic landscape and ethnographic record. Moreover, much of Headford persists as an agricultural community featuring grazing pastures surrounded by bounding trees and/or walls so the locations of these features in relation to the cillíní have likely been relatively consistent since the nineteenth century.
As described in Chapters 4 and 5, the spread of sound and modeling of estimated soundsheds are dependent on several environmental factors, including temperature and humidity, and, therefore, it is important to situate modeling scenarios temporally. Initially, two dates were chosen for modeling: October 31 and May 1. Traditionally, the Irish Folk calendar celebrated the start of each season with a festival: February 1 marked the coming of Spring with Lá 'le Bride; May 1, Beltaine at the start of summer; on August 1, Lúnasa the beginning of Autumn; and the arrival of winter with Samhain, November 1 (Danaher 1981:217-8). These dates signified not only the changing climate patterns, but were also times that rents were due, contracts were written, and farmers or fishers altered their daily tasks. Thus, the festivals held on these dates celebrated the liminality between changing seasons, and at these times divination was practiced and supernatural forces were active (Danaher 1981:218-20). May 1, or Beltaine, marked the first day of summer, a time of life and abundance. This began the main dairy season, and was a particularly active date for supernatural beings. November 1, or Samhain, was considered the end of the Irish year, and was a liminal time when it was easier to move between the spirit world and the world of the living. Souls of the deceased would visit their households, and in more recent times Samhain became celebrated as Halloween (Danaher 1981:218-20; Primeau et al. n.d: 9). Burials within the Headford cillíní lacked specific dates, therefore, October 31 and May 1 were chosen to further represent the role of liminality in the conceptual landscape of historical Ireland. If the sites in the study area were visited or used on these dates, audible experiences may have further contributed to an understanding of these places as off-limits or even otherworldly (Primeau et al. n.d: 9-10).
Climate data for October 31 and May 1 was available from the Irish meteorological service, *Met Éireann* (Met Éireann 2018), including hourly readings from the Claremorris weather station, located approximately 24.7 km northwest of the study area that dated back to 1988. Using this data, hourly average temperatures and relative humidities were calculated. Then a correctional factor of 0.85 °C was subtracted from the average hourly temperatures to account for climate change according to long term temperature trends calculated by *Met Éireann* (Gleeson et al. 2013) and the Intergovernmental Panel on Climate Change (2014).

Two scenarios were explored to better understand the soundscapes of mourning and remembrance at *cillín*: (1) a man speaking at dusk on October 31, and (2) church bells ringing at approximately 4:00 p.m. on May 1. As noted above, burials at *cillín* would have taken place at night and thus the first scenario is representative of the established visitation patterns in these locations. Dusk also represents the threshold between day and night, and further emphasizes the liminality of the transition from intrusive colonial practices and traditional Irish practices, between the outward front and the secretive belief.

While the initial goals for this study posited to model scenario one on both dates, it was discovered that, interestingly, dusk was likely to be equally chilly. The average temperature of both evenings measured within a fraction of a degree of each other: approximately 9.05 °C (46.76 °F) at dusk on October 31 (approximately 5:32 p.m.), and approximately 8.85 °C (46.4 °F) at dusk on May 1 (approximately 9:35 p.m.) (Met Éireann 2018). At dusk, a reduction in activities which generate outdoor sounds would result in
lowering of the ambient sound levels (modeled at 23 dBA), and the high relative humidity (87.5% on October 31) would result in a feeling of dampness settling in. This, combined with a reduction of temperatures, causes sound to spread further than it would on a warm afternoon (Lamancusa 2009). Because of the similarity in climate at dusk on these two dates, all modeling of sounds produced by a man speaking was subsequently completed using the data for October 31.

A male speaker was chosen for soundshed modeling because folk tradition and ethnographic data suggest that male family members were primarily responsible for the burials (Finlay 2000:403; Murphy 2011:416; see also: Garattini 2007; O'Sullivan & Sheehan 1996; Sugrue 1993). In addition, Irish women generally underwent a period of confinement following a birth, ranging from approximately nine days to two weeks of isolation and prescribed reduction in normal activities, and as a result were unlikely to be present at the burial if the child was stillborn or passed shortly after birth (Murphy 2011). Data regarding male height were gathered from a review of Irish osteological data performed by Jennifer Shaffer Foster (Primeau et al. n.d: 10; Young et al. 2008), and data concerning sound pressure levels of male speech were researched by David Witt and myself (Byrne et al. 1994; Hayne et al. 2006; Monson et al. 2012; Primeau et al. n.d: 10). Murphy (2011) “argues that interment in a cillín was often undertaken with similar rituals and importance to the family as interment in consecrated ground (Primeau et al. n.d: 10).” Therefore, in scenario one a man speaks in a low voice as an infant is buried. The sign of reverence indicated by the sound of a low voice (modeled using 55 dBA, emanating from his mouth at approximately 5 ft. above ground surface) would also be expected at
other religiously charged locations; as a result, soundshed modeling was completed for a variety of sites, including cillíní, raths, and the Protestant vicarage.

For the second scenario, the sound of the church bells would have called worshipers to late afternoon Protestant services—services that would have excluded those whose conceptual landscape included cillíní. Climatological data was collected using the same procedures for both scenarios. At 4 pm on May 1 the average air temperature was approximately 13.3°C (55.94 °F) with a relative humidity of 67 percent. Data regarding the height, fundamental frequency, and sound pressure levels of the ringing church bell were gathered from relevant literature (Fletcher and Rossing 1998; Omlin and Brink 2013) and DSMs (Bluesky Mapshop Ireland 2018). Only one church recorded in the National Monuments Service records was located within the project area, so modeling of the second scenario focused on a single site (National Monuments Service 2017).

The Soundshed Analysis Tool was used to model the estimated spread of sound from 11 locations. Seven of these, discussed below, were selected to further explore the importance of sound within the cultural landscape of Headford, County Galway. These sites include four cillíní, a cashel lacking a children’s burial ground, a Protestant church, and its associated vicarage. Additional modeling results are available in Appendix F.

Site GA 042-204001 described as “Rath with Souterrain Tradition” is a cillín within an ellipsoid rath measuring approximately 50 m by 40 m (see Figure 9.2). The rath is characterized by a “low curving scarp” to the northeast which extends approximately 25
cm above grade, and a shallow dip along its western edge (Alcock et al. 1999; National Monuments Service 2017). By 1920, GA042-204001 appeared on Ordnance Survey maps (Alcock et al. 1999; National Monuments Service 2017). National Monuments Service records state that “according to the landowner, there was formerly a 'tree' in the interior which his father would not touch. He also had the tradition of a 'cave' in the same area: 'a hollow sound' has also been heard c. 60 m to NNE, in the adjacent field, during ploughing (National Monuments Service 2017).” This cave is interpreted as a possible souterrain, an underground passageway or chamber common to later phases of rath occupation. They could be created by digging large pits or trenches and tunneling horizontally, lining the walls and roofs with stone or wood. They are believed to have provided shelter if the settlement was under attack, and also functioned as storage spaces (Edwards 2005: 249-52). In Irish folklore, caves were also associated with the underworld and were themselves liminal places (Primeau et al. n.d.: 12).

Though the central tree is no longer extant, GA 042-204001 is bounded by a row of trees to the south and a smaller perpendicular row of trees along the site’s western edge. As seen in Figure 9.2, the presence of these trees diffuses the sound of the man’s low speech, which can be heard for 14.8 m; however, to the north and east of the site, his voice could be heard for approximately 37.5 m, unimpeded by topography or landscape features.
Site GA 042-185001 is a rath that, according to Ireland’s National Monuments Service, was plowed out in the 1950s (National Monuments Service 2017). However, it is still visible in aerial photography and had a reputation as a children’s burial ground (Alcock et al. 1999; National Monuments Service 2017) (see Figure 9.3). A map from 1920 depicted the rath as a circular enclosure with a diameter of approximately 25 meters. The enclosure is also listed as potentially bivallate, which appears to be consistent with
the size and shape depicted in aerial photos (Alcock et al. 1999; National Monuments Service 2017).

In contrast with GA 042-204001, GA 042-185001 is located in an area devoid of vegetation, instead featuring one of the stone walls common to the Headford landscape. The boundaries created by the wall surrounding this *cillín* were likely in place by the nineteenth century as the adjacent land belongs to a vicarage constructed around 1820. Here, a man’s low voice can be heard in almost every direction for a distance of 37.5 m,
with the exception of the southeast of the site where the wall and topography impede sound transmission (see Figure 9.4). As described above, this site has been plowed out, therefore, some additional transmission losses could be expected had the rath retained more of its vertical extent.

**Figure 9.4:** Estimated soundshed of a man speaking at GA 042-185001

Site GA 042-042001 is a rath that is associated spatially with two other sites: GA 042-043001, another rath; and GA 042-044001, described as a “ringfort-cashel” (National Monuments Service 2017). Due to their close arrangement, these sites are discussed
together here. Contemporaneous with raths, cashels featured stone walls rather than earthen ones, and often lacked surrounding ditches. Univalliate cashels often enclosed a slightly smaller area than their rath counterparts (Edwards 2005:242). There is no evidence for GA 042-044001 having been used as a children’s burial ground, however, both GA 042-042001 and GA 042-043001 were identified as *cillíní* prior to the creation of 1920’s ordnance survey maps which list them as such (National Monuments Service 2017).

Figure 9.5 shows the estimated soundsheds of a man speaking from each of these three sites superimposed on the same map. Note that this is *not* acoustically representative of a cumulative soundshed as would be expected to result for three men speaking, one in each location, at the same time. Rather, this figure is only intended to illustrate the spatial extent to which sound would travel from each of these three sites for discussion purposes. It is interesting to note, that while the soundsheds from sites GA 042-043001 and GA 042-044001 would overlap, there is no overlap between the estimated soundsheds for GA 042-042001 and GA 042-043001 as will be discussed later.

Site NIAH #30404212 is a vicarage located almost equidistant from sites GA 042-204001 (located 349.3 m to the west) and GA 042-185001 (located 349.7 m to the southeast). This vicarage was constructed by the St. George family between 1810 and 1830 and is associated with the protestant Church of St. John the Baptist.
Figure 9.5: Estimated soundshed of a man speaking at GA 042-042001 shown concurrently with the estimated soundsheds of a man speaking at GA 042-043001, and GA 042-044001.

(Site GA042-120) (National Inventory of Architectural Heritage 2018a). The vicarage is described as “a typical Church of Ireland glebe house of the early nineteenth century with the wide eaves of the period (National Inventory of Architectural Heritage 2018a) (see Figure 9.6).”
The sound source modeled at the vicarage also consists of a man speaking on an October evening (see Figure 9.7). He stands outside to the northeast of the structure, near an adjacent driveway. The dwelling prevents most of the sound of his voice from spreading towards the two *cillíní*, and the remaining sound transmission is restricted by a wall which borders the driveway to the east. This confines the majority of his speech to a radius of approximately 26 m, not taking into account source directivity.

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44 This image is published at: http://www.buildingsofireland.ie/niah/search.jsp?county=GA&regno=30404212&type=record. It is used for educational purposes courtesy of the National Inventory of Architectural Heritage and is copyright of the Department of Housing, Local Government and Heritage.
Site GA 042-120, the Church of St. John the Baptist, was first constructed in the late seventeenth century and improvements to the church continued during the eighteenth and nineteenth centuries, including the “three-stage tower of c.1740,” and “four-bay nave of c.1830” (Hannon 2015; National Inventory of Architectural Heritage 2018b) (see Figures 9.8 and 9.9). The churchyard is surrounded by the remnants of a limestone wall, which enclose a graveyard, and although the church is now in disrepair, worship
continued there through 1966 (Hannon 2015; National Inventory of Architectural Heritage 2018b).

**Figure 9.8:** Front of the Church of St. John the Baptist, Showing Bell Tower and Limestone Wall

![Image of Church of St. John the Baptist](http://www.buildingsofireland.ie/niah/search.jsp?type=images&county=GA&regno=30404216)

Currently, the Soundsheard Analysis tool models sound using formulae for outdoor sound propagation only, therefore, the GIS model does not yet allow a sound source to be placed within an enclosing structure. To address this limitation, church bells were modeled as if unimpeded by the walls of the tower in which they were located; in other

45 This image is published at: [http://www.buildingsofireland.ie/niah/search.jsp?type=images&county=GA&regno=30404216](http://www.buildingsofireland.ie/niah/search.jsp?type=images&county=GA&regno=30404216). It is used for educational purposes courtesy of the National Inventory of Architectural Heritage and is copyright of the Department of Housing, Local Government and Heritage.
words, as if they were on top of the bell tower. Each of the four walls of the limestone tower featured a segmental-headed window (National Inventory of Architectural Heritage 2018b), therefore, some transmission losses would have occurred as a result of the surrounding walls but are not captured here.

**Figure 9.9:** Rear of the Church of St. John the Baptist

The church is located in the southeastern portion of the study area (see Figure 9.1). While this does not impede the overall functioning of the soundshed tool, it does limit the results to the area for which input elevations (DSM data) were available. The

46 This image is published at: [http://www.buildingsofireland.ie/niah/search.jsp?type=images&county=GA&regno=30404216](http://www.buildingsofireland.ie/niah/search.jsp?type=images&county=GA&regno=30404216). It is used for educational purposes courtesy of the National Inventory of Architectural Heritage and is copyright of the Department of Housing, Local Government and Heritage.
estimated soundshed indicates that without intervening sounds, the sound of the church bell has the potential to be heard above the ambient background for a distance of 2.57 km; however, simulations indicate that if the study area were unrestricted, the sound of the bell could potentially spread for a greater distance unless blocked or absorbed by barriers (see Figure 9.10).

**Figure 9.10:** Estimated soundshed of a church bell ringing at GA 042-120, the Church of St. John the Baptist
As indicated above, a tension existed between the Protestant St. George family and their traditional Irish tenants. Indeed, according to documentary evidence, a Catholic church was finally built in County Galway during the mid-nineteenth century (Galway County Heritage Office 2017). This tense relationship is paralleled by interpretations of the modeled soundshed of the church bells and location of *cillíní*. Of the seven known children’s burial grounds within the study area, only one, GA 042-185001, is situated within the area in which church bells might be heard. While this site was located on the edge of the soundshed, it experienced a noticeable sound pressure level increase of just over 16 dBA above the ambient sound levels projected for this scenario. Additionally, GA 042-204001 is located immediately beyond the modeled soundshed; it is within one meter of an area where bells would be expected to produce around 15 dBA over the background sound level, therefore, it is likely that the bell could be heard at GA 042-204001. In other cases, such as at sites GA 042-042001 and GA 042-043001, intervening topography and vegetation attenuates the sound of the bell, indicating that under the conditions of this modeling scenario, people located within these *cillíní* would not have experienced much, if any, of the bell’s ringing.

**Review and Discussion**

The sonorous environment within nineteenth- and twentieth-century Ireland included religiously charged elements punctuated with traditional folklore. As evidenced by the Schools Collection, the Irish landscape was more than a “simple surface for action….divorced from any consideration of structures of power and domination” (Tilley 1994:9). The landscape shaped, and was shaped by, actions as noted in recorded
accounts of avoidance or reuse of sites. Indeed, the importance placed on collecting and preserving the stories about cillíní is itself telling of the memories and identities that the landscape contributed to forming.

Shaffer Foster states, “Cultural mores dictated that raths were to be left alone, and thus their reuse as children’s burial grounds was a way to impart reverence to the loss of a loved one excluded from customary religious rites (Primeau et al. n.d.:16).” In other areas, those with liminal status were buried as close as possible to consecrated ground. Lindow writes:

"To be close to the church was higher status than to be farther away, and the southern and eastern portions were the areas more often used, in accordance with the privileging of these directions in Christian doctrine in Europe. Indeed, the north side of the churchyard might be shunned, and the place to put those whose salvation was in doctrinal question, such as unbaptised infants and suicides, might well be on the north edge of the churchyard. The liminality of the churchyard was thus obvious." (Lindow 2018)

Galway County Heritage Office records indicate that residents of the county wanted a separate place for worship and burial, but a Catholic church and churchyard weren’t constructed in Headford until late in the historic period (Galway County Heritage Office 2017). Even Catholic Irish who received the proper sacraments may not have had access to consecrated burial grounds in this area during the nineteenth century. How did
the landscape reflect the contestation of community religious beliefs versus those of the landowners? As asked above, how did the acoustics of the Protestant faith manifest in the greater landscape? How would conflicting religious ideologies have impacted the already heterodox burials of infants and children within *cillíní* undertaken by Catholic families in a place where the church and churchyard represented colonial religious ideology?

As indicated by the estimated soundsheds, rituals of burial and mourning could be heard within the greater landscape, and it appears that nineteenth-century Irish families in the Headford area considered audibility when locating children’s burial grounds, perhaps as a managed aspect of secrecy or privacy. Figures 9.2, 9.4 and 9.5 above, as well as Figures F-1.1, F1.2 and F-2.1 contained in Appendix F illustrate that voices of those interring the dead, or grieving at grave sites, were largely contained within *cillíní*. Other raths, cahsels, and enclosures which were not used as *cillíní* also effectively limited sounds (See Figures F-1.3 through F-1.6) so it is probable that the isolation of these sites was commonly known. Figure 9.5 is particularly telling when trying to ascertain whether sound was a factor in siting *cillíní*. Here, though the remains of three early-medieval domestic structures are present, only two were reused as burial grounds. The estimated soundsheds for Sites GA 042-042001 and GA 042-043001 (both of which contain *cillíní*) are isolated from one another, while the sound of a man speaking would have been interaudible between Sites GA 042-043001 and GA 042-044001, the latter of which was not used as a *cillín*. Though each of the three sites in Figure 9.5 effectively contained
sounds, only the combination of Site GA 042-042001 and either GA 042-043001 or GA 042-044001 would have resulted in acoustic isolation, an echo of liminal site placement.

The second objective of this study was to explore the impact of colonial religious practices on traditional Irish Catholicism and in particular, use of *cillíní*. Discretion as achieved through management and containment of sound would have been important in a landscape that was controlled by those with a different belief system. Returning to Figure 9.9, all *cillíní* were located at the periphery or beyond the lands dominated by the sound of the Protestant church bell. Only GA 042-185001 and perhaps GA 042-204001 would have been close enough to provide an opportunity for those gathered within to monitor the surrounding landscape’s soundshed while keeping their own activities safely bounded within traditional or politically neutral places. In Headford the sounds of the church bells and vicarage were related to the imposition of both English religious practices and English landscape organization. As Mileson states, “bells were a key element of the individual’s experience of religion, and there are strong indications that they also helped shape a sense of connection with place” (Mileson 2018:719). In this contested landscape, church bells would have been a recurrent reminder of the presence of English forces and all the asymmetrical power relations they entailed (Nickleson 2016), however, this did not deter the Catholic Irish from utilizing the landscape for their own purposes. Placement of *cillíní* on the very edge of the church’s soundshed, may indicate the degree to which the Irish attempted to avoid English influence. For the Catholic Irish living in a colonized, Protestant landscape, control of sound enabled the continuation of religious and mortuary
practices while also, perhaps, embodying a silent protest against those in power (Primeau et al. n.d.:17).

Reflection and Conclusion

As stated above, following the reforms of Vatican II (c.1965 CE) the Catholic Church relaxed its view on purgatory and as Dennehy describes, “strongly disassociated” with the ideas of Children’s Limbo which for centuries, resulted in separate burial in unconsecrated ground for those with liminal status. However, as Shaffer Foster reminds us *cillíní* and other liminal burial locations within the Irish landscape persist in living memory as places of mourning; “*Cillíní* and the practice of separate, secretive, burials, still exert powerful, traumatic holds over the cognitive geography of many Irish people (Primeau et al. n.d.:17).” Martine Brennan, an Irish woman and genealogy researcher, relates her very personal experience:

“In 1969 my mother gave birth to my brother Michael. He died at birth.

. . . As was the custom, my grandfather and my father took Michael from my mother and buried him against the walls of the ruined church in the old graveyard… Michael had died before baptism so he was excluded from a Catholic burial in the family grave. My mother was not told where Michael was buried. Custom forbade her from speaking of him. It was as though the waters closed, leaving no trace of my brother. My mother gave birth to three more children, only one of whom survived birth. Out of six of us siblings, only three survived birth.
How did my mother not go completely mad? How did she cope with six fear filled pregnancies?... How did she live in a community in which speaking of her beloved babies was forbidden? How did she continue to attend a church that would not acknowledge her babies and excluded them, and her, from its consolation ...?

A few months before my grandfather died, he told my mother where Michael is buried. Thirty years after Michael's birth and death, my mother was finally able to mark Michael's life and approximate burial place with a small marble plaque. With this simple act, she found a measure of peace...

The secrecy around my siblings births, deaths and furtive burials caused untold harm to my parents and our family life. Anguish was always just below the surface. Like a simmering soup, bitterness festered in the background. I grew up feeling their pain but not understanding it (Brennan 2012).”

Murphy, reflecting upon the study of cillíní and child loss, states that “the archaeology of emotion has been largely ignored (2011:411).” Her work confirms that as Brennan describes, the topic of children’s burials has historically been a private one; secret, exclusionary, and silenced by custom. While phenomenological study has largely

47 This passage has been reproduced with the author’s permission, and I take a moment here to thank her once again for allowing us to share in her family’s very personal experience.
focused on monumental landscapes, the sounds created and experienced at Headford’s *cillíní* were quiet, intimate, and arguably manifested an unparalleled monumentality of their own. As discussed, ethnographic evidence suggests that an aura of reverence persists around these sites, and that the *cillíní* still very clearly impact memory, identity, and experience as they undoubtedly did in the nineteenth century. Following Merleau-Ponty’s concepts of perception and subjective consciousness (Merleau-Ponty 1962) and Tilley’s concept of “the Being of the body in the world,” (Tilley 1994) the individual is hearing and perceiving via other senses, thus reconciling their own identity with that of their place in their family, with their family’s actions, and with the landscape in the context of traditional mores.

*Cillíní*, in the context of nineteenth- and twentieth-century Ireland, were the very definition of liminal places. More than half of Ireland’s *cillíní* were collocated with archaeological sites, many of which were raths (Dennehy 2016:222). Raths, abandoned generations before their reuse as burial grounds, were traditionally held to have connections with the “other world” of fairies, changelings, and supernatural beings, and as such were places to be avoided (Finlay 2000:411-2). This sacred but unconsecrated ground protected the children buried within from disturbance, and isolated the Catholic religious practices surrounding *cillíní* from a landscape of Protestant colonial influence. The estimated models of the acoustic environment presented in this chapter show that *cillíní* were located at the periphery of or beyond the Protestant church bell soundshed, placing them within liminal acoustic areas as well.
Although Ireland achieved political, social, and religious autonomy following the First World War, burial in *cillíní* continued to occur for another 50 or more years, remaining a secretive and somewhat shameful practice. As a result, *cillíní* and the burial traditions surrounding them were not widely discussed, and yet, as Brennan’s writing shows, clearly resulted in intergenerational trauma. Shaffer Foster writes that, “in the past few decades, various scholars, individuals, and organizations within Ireland (H.U.G. Alliance 2012) have begun trying to ease this emotional burden for the family members of those buried within *cillíní* by having these sites formally recognized as burial grounds and important places for mourning (Primeau et al. n.d.:19).” Understanding the sound transmission potential within and around *cillíní* while they were in use during the nineteenth and twentieth centuries tells us much about the lived experience of those who visited them, those who interred beloved family members within them, and those who conceptualized these as places of secretive sorrow. For those still affected by these sites today, as Brennan notes, mourning is not just for those lost, but for those who endured (Primeau et al. n.d.:19).
Chapter 10. Discussion, Recommendations, Conclusions

Like visibility, audibility can be an actively managed aspect of the built environment, and one can question the relationship between sound and site in the landscape. The case studies presented in the preceding chapters exemplify how sound was used to include, exclude, manipulate, reify, engage, and revere individuals or groups of people as a facet of religion, ritual, political power, and culture. From the spectacle of Chacoan political theater to the intimacy of mourning in Ireland, human action is a multisensory experience and is long due to be aurally contextualized as part of a broader anthropological archaeology.

The Soundshed Analysis Toolbox, when coupled with an anthropological archaeology approach, allows researchers to more fully understand how past landscapes were experienced by those who lived there, answering Tim Ingold’s call that anthropologists adopt a greater awareness of the lived experience (2000). The soundscape archaeology approach presented here offers an opportunity to respond to critiques of positivistic uses of GIS. In addition, it further integrates phenomenological methodologies within landscape studies, and allows researchers to begin exploring audible spaces as heard places.

Words of Caution – GIS Based Soundsheids are Estimations

Like any modeling tool or software, the Soundshed Analysis toolbox creates estimations. These estimations are subject to input biases based on the quality of data entered by and available to the researcher. The analyses presented in Chapters 7-9
utilize modeling inputs primarily derived from literature searches, such as the dominant frequency (in Hz) of culturally produced sounds, sound pressure levels (in decibels or A-weighted decibels), and other inputs. Historical climatological data is also used by proxy to derive certain model inputs (temperature, relative humidity), some with noted correctional factors applied (see Chapter 9). Additionally, the use of modern LIDAR or elevation datasets may skew modeling results; modern features, such as roads or buildings, could affect how sound spreads throughout the landscape (see Chapter 7, figures 7.7 through 7.9 for examples). Use of digital surface models rather than digital terrain models may also skew results. Finally, certain complexities of sound physics that are difficult to model in GIS cause inherent limitations within the soundshed modeling tools, including canyon effects and reverberation which require greater ability to characterize materials, semi/enclosed spaces, and angles of incidence relative to surfaces/materials than the program currently provides.

A full spectrum approach to the archaeological method requires the application of multimodal methodologies, and, therefore, a soundscape archaeology approach is not intended to consist of modeled soundsheds in isolation of appropriate context (a point to be discussed further in “Recommendations” below). However, it is also the responsibility of the researcher to educate themselves as to how the tools function, and to appropriately situate their modeling inputs in a cultural context. The logical timing of an ancient sound producing event aside, one must understand the impact, for example, of modeling sound on a cool night versus a warm summer day. Archaeologically speaking, approximating the temporal and climatological factors surrounding an event may prove difficult, but as
more researchers provide data on the acoustic properties of reproduced or past instruments and voices (e.g., Boren et al. 2013; Kolar et al. 2018:15, Table 1; Loose 2012; Taylor et al. 1994) the ability to model past soundsheds is growing. A GIS approach to landscape scale archaeoacoustics provides a contextualizing framework by which researchers can approach auditory hypotheses, explore embodied experience, and listen to what the past is telling us.

**Ongoing Development and Future Directions**

Understanding the limitations of the current Archaeoacoustics Toolbox, as described above, the goals of this research are ongoing. With the release of ArcGIS Pro and upon review of other available technologies, particularly those with true 3D modeling and surface material characterization capabilities, it may be possible to create alternate workflows that may allow more computations to take place outside of arcpy and/or ArcGIS. One of the original goals of this project, to keep the Toolbox open source and easily accessible to a variety of archaeologists and researchers, is at the core of this mission, but so too is further advancement of the tools’ functionality.

Given expanded geoprocessing capabilities, three immediate directions for future work arise. First, is the incorporation of directional sources and directivity in modeling. When a person speaks or plays certain directional instruments, such as a trumpet, the direction of the individual’s mouth or the bell of the instrument effects the outward propagation of sound at certain frequencies (Katz and D'Allesandro 2007; Pätynen and
A highly directional source would produce different estimated soundsheds than an omnidirectional source of the same sound pressure level, and this can be calculated through incorporation of a directivity index (Long 2006:68). This improvement in modeling capability would also require greater characterization of the sound source, which may require additional data collection when studying soundsheds produced by instruments of the past (e.g., flutes, conch horns, etc.).

A second consideration is that of wind effects. It is known that the weather effects the propagation of sound (see Chapter 4), however, unless a site is notable for its wind regime, the effects of wind are typically discounted when studying site archaeoacoustics (Díaz-Andreu and García Benito 2012:3594). Kolar et al. have demonstrated that in certain high elevation sites, such as Huánuco Pampa, gusty conditions may have contributed to the selection of a particular sound producing device to intentionally convey or contain sound (2018:22). Wind speeds typically increase as height above ground levels increase resulting in a bending of soundwaves that effect propagation. For example, Foss has shown that at a height of 1.22 meters, 16 kph winds traveling in the same direction as the sound (i.e., parallel to sound transmission) resulted in a 10 dB increase in SPLs at higher frequencies when compared to zero wind, and 8kph winds opposite the direction of the sound resulted in a reduction of SPL by approximately 7 dB (1979:1091). Below approximately 500 Hz ground and surface effects dominate over the effects of windshear (Foss 1979:1091-2). Like the Soundshed Analysis – Variable Cover

48 This is based on the proportion of the source dimensions, such as the bell of a trumpet, to wavelength (Beranek 1993:93; Pätyinen and Lokki 2010:149).
tool, a version of the Soundshed Analysis tool which accounts for the effects of wind would be a welcome addition to the Toolbox.

A third improvement for the Archaeoacoustics Toolbox is the Cumulative Soundshed tool, which is currently under development. Although a single sound source may be common in ritual, ceremonial, and monumental contexts, everyday sounds may originate from a variety of sources and locations simultaneously. For example, crowds in various plazas might all contribute to the soundscape of an area. Could a person shouting from a distant location be heard over the din? The additive effect of concurrent sounds is calculated logarithmically rather than arithmetically, therefore, a different tool is required to explore concomitant soundscapes. When adding two sound sources of the same decibel level, even two 0 dB sources, an increase of 3 decibels is experienced instead of a perceived doubling in sound pressure; whereas, when adding sound pressure levels that vary by 10 or more decibels, no increase above the higher pressure sound will be heard (Cowan 1994:31-2). The Cumulative Soundshed tool will model based on this principle and function by combining various output layers produced by the Archaeoacoustics Toolbox into a single raster dataset. Future releases of the Soundshed Analysis Toolbox will include the Cumulative Soundshed tool and any further enhancements.

Recommendations

The Archaeoacoustics Toolbox is intended to be used by archaeologists and anthropologists wishing to gain a better understanding of what was heard in the past.
While it does not necessarily require a background in acoustics, some basic understanding of sound physics is helpful for understanding the way that sound propagates and is quantified. A primer has been presented in Chapter 4 which is meant to provide introductory reading on the topic. The recommendations below are meant to help a researcher determine whether the Archaeoacoustics Toolbox would provide a complementary methodology to assess their sonic hypotheses, as well as to help foster a research design using the tools.

As a general rule, all archaeoacoustic study can benefit from the inclusion of the input of descendent communities; ethnographic or ethnohistoric components; or in absence of this, ethnographic analogy (e.g., Howes 2008; Hymes 1975; Inomata 2006; Kolar 2013, 2017; Kolar et al. 2018; Moore 2006; Scullin 2015; Scullin and Boyd 2014; Till 2014). As previously discussed, I find Howes’ tripartite approach provides a firm foundation from which to begin, and from which to frame one’s consideration of the modeling results. Howes suggests: “(1) observing the sensory characteristics of a culture, (2) understanding those sensory characteristics in their own cultural context, and (3) interpreting and analyzing the collected material in a broader cultural... perspective (Howes 2008:445).”

Archaeoacoustics research design also benefits from fieldwork, before and throughout the process. Fieldwork not only provides background data relevant to acoustic conditions (e.g., sound producing devices, primary texts, iconography, population densities, vegetation characteristics, settlement layouts, etc.); but also includes reconnaissance to determine the most appropriate locations for modeling, and ground-
truthing of field conditions which may impact the spread of sound, such as a modern visitors center building which is present in the LiDAR point cloud. Finally, a research design should include methods to produce and evaluate sounds in the field following established scientific methodologies when it is possible to do so (e.g., ANSI 1973, 1988, 1994, 1995, 1997, 1998; Cross and Watson 2006; Díaz-Andreu et al. 2014, 2017, 2019; Díaz-Andreu and García Benito 2015; Mattioli et al. 2017; Mattioli and Díaz-Andreu 2017; Iannace et al. 2013, 2014; Iannace and Trematerra 2014; Iannace and Berardi 2017; IEC 2003, 2013; ISO 1991, 1993, 1996, 2007, 2008, 2009, 2012, 2014, 2018; Kolar 2013, 2017; Kolar et al. 2018; Liwosz 2018; Till 2014). In some cases this may be prevented due to a lack of extant structures, or an intrusive modern sound environment. Fieldwork can be used to identify site-specific acoustic effects, such as flutter echoes, standing waves, and unusual focal properties, which are not captured within the estimated soundsheds produced using the Archaeoacoustics Toolbox (e.g., Jahn et al. 1996; Kolar 2013, 2017; Loose 2008; Stein et al. 2007; Watson 2006; Watson and Keating 1999).

In consideration of the above, a research design implementing the Archaeoacoustics Toolbox should involve the following steps:

1. **Evaluate your research questions:** Some examples appearing in Chapters 7-9 include:
   
a. Could performance spaces be identified within the Chacoan landscape? Where could specific outdoor events be heard?
b. Were Chacoan sites located in areas that marked the boundaries of performance space? Does the built environment provide evidence that audibility may have played a factor in site placement?

c. Who could see or hear the performance as Copán’s Ruler 13 walked from stelae to stelae? Were some people able to do both? What might the results tell us about Maya performance and its intended audience?

d. How did the atmosphere of performance spaces change when Copán’s final dynastic king, Ruler 16, commissioned new buildings in the Acropolis? How were the visibility and acoustics of ritual performance affected?

e. Could rituals of burial and mourning performed within cillíní be heard within the greater landscape? Is there evidence that the spread of sound may have been managed or contained?

f. How did the acoustics of the Protestant faith manifest in the greater landscape? Is there evidence that cillíní were placed in locations where the acoustic envelope remained traditional or politically neutral?

Review the research question to determine whether it is a good candidate for modeling. Bear in mind that the tools within the Archaeoacoustics Toolbox model outdoor sound propagation only. If, for example, your research asks whether sounds produced within an enclosed kiva could be heard from an external location, or whether the lake adjacent to a domestic structure would cause sound to reverberate in a characteristic fashion, your study would be better served by an alternate approach. If
it remains unclear whether modeling is possible for your chosen question, first consult Chapters 4-6, then begin to assemble input data. In some cases a lack of available data may be the limiting factor.

2. **Choose a modeling scenario:** A hypothetical scenario helps direct data collection for modeling location, sound source characteristics, and climatological data, situating the study in place and time. Consider the importance of the time of year and time of day in which your sound producing event “occurs.” Is it tied to a specific ritual, season, or date, or does it occur ubiquitously? Consider your sound source – is sound produced by instruments, people, or both? Are the instruments played by professional musicians, or were they widely distributed? Are the songs or spoken word of interest produced exclusively by children, elders, men, or women? If possible, speak with descendent communities, consult ethnohistoric accounts, research primary texts and/or iconography to accurately construct your scenario from an *emic* perspective. Your modeling scenario will also be shaped by your theoretical approach.

Once this is complete, determine whether there are climatological records available which are representative of, or which can be corrected to represent your chosen scenario. Also determine whether appropriate acoustical data regarding a sound source exists. As further described in Appendix G, the Sound level of the source (dB), its dominant frequency (Hz) and the measurement distance (ft) at which these were recorded are inextricably connected. These three factors must be published within the same reference material (e.g., within a single article or chapter), or they must be measured contemporaneously in the field. If fieldwork is required, care must
be taken to try to record measurements on a clear quiet day. Wind and other background noise can impact acoustical data. ANSI S12.18 (1994) presents the methods for properly collecting acoustical data.

3. **Choose a modeling location:** This consists of both a point location within the landscape, and available elevation data suitable for modeling. The tools in the Archaeoacoustics Toolbox can function using a variety of elevation models with resolutions varying from 100 ft. squares to 1 meter squares, however, the output resolution is directly tied to the input resolution, therefore, higher resolution data, such as LiDAR will produce more detailed results.

   Point locations used in modeling must be situated in outdoor areas; enclosed or semi-enclosed areas will impact modeling results. Point locations will draw their elevation values directly from the elevation dataset beneath. While it may seem possible to bypass the lack of an extant structure within a modern elevation dataset by artificially inflating the height of the sound source, this is not the case. The tools will estimate how sound spreads out from the source over the existing terrain within the elevation dataset, providing an inaccurate modeling result which will appear to include more areas within the soundshed than would have been included in the past. To model past soundsheds where structures are no longer extant, elevation reconstructions and structure locations within a 4.0 kilometer (2.5 mile) radius must be produced prior to modeling (e.g., Agugiaro et al. 2011; Goodwin and Richards-Rissetto 2017; Lyons 2016; Remondino et al. 2009; Richards-Rissetto 2010, 2013; Richards-Rissetto and Plessing 2015; von Schwerin 2011; von Schwerin et al. 2016).
4. Determine which tool to use in consideration of your research question, scenario, and modeling location. The Soundshed Analysis Tool models how sound spreads throughout a landscape and assumes a constant ambient Sound Pressure Level (SPL) throughout the entire study area. It is best suited for modeling in open homogenous terrain, such as desert, plains, cleared agricultural land, or other areas where vegetation generally does not break the line of sight. By comparison, the Soundshed Analysis – Variable Cover Tool is best suited for modeling in areas of diverse ecotones. The Variable Cover Tool also includes the optional assignment of multiple ambient SPLs which can be based on cover type, or unrelated entirely such as pockets of differing ambient SPLs in areas of open terrain (e.g., higher ambient SPL areas near a stream on a plain).

An evaluation of whether to use the Variable Cover Tool will also include answering the questions of whether extant vegetation is historically accurate, or if land cover must also be a reconstructed feature. Was the study area densely vegetated in the past? Was it cleared, or did it consist of cropland? These questions must be addressed in a research design. Use of the Variable Cover tool requires the preparation of a “Vegetative Cover Type” layer as described in Appendix G.

5. Determine Ambient Sound Pressure Levels: either from literature reviews or via the methods for collecting acoustical data in the field described in ANSI S12.18 (1994). If fieldwork indicates that the ambient SPL varies throughout the minimum 4km radius study area surrounding the modeling location, but that the landscape itself was fairly homogenous, this can be modeled using the Soundshed Analysis – Variable Cover
Tool where the “Vegetative Cover Type” layer consists of a single value, such as cover type A for an open desert landscape.

6. **Run the Model.** In consideration of the previous steps, this research design will produce all of the required inputs for modeling. A detailed technical discussion of inputs can be found in Appendix G.

**Finale**

One needs only consider the often quoted philosophical thought experiment: “if a tree falls in a forest and no one is there to hear it, does it make a sound” to understand the importance of human perception and experience to our understanding of sound. Without the human element, a falling tree merely produces an assemblage of waves, vibrations, and pressure, devoid of context. Sound and sensory perception were as much a part of past experience as they are part of our world today, and an archaeology without sound is like a falling tree without a listener. Anthropological and archaeological context can inform and be informed by which sounds were intrusive, revered, or ignored; and which soundsheds contained intrinsic significance at a moment in time. The Archaeoacoustics Toolbox establishes methods to model and explore the estimated spread of sound throughout anthropogenic landscapes, providing access to an intangible perishable resource, and the tools with which to do so.
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Appendix A: A Comparison of the Functionality of SPReAD-GIS (Reed et al. 2009; Reed et al. 2010) to the Soundshed Analysis Tool

<table>
<thead>
<tr>
<th>Function</th>
<th>SPReAD-GIS (Tool #2)</th>
<th>Soundshed Analysis Tool</th>
</tr>
</thead>
<tbody>
<tr>
<td>General Syntax</td>
<td>Written in ArcPy for use in an ArcGIS 9.3 environment.</td>
<td>Written in ArcPy for use in an ArcGIS 10.3 (or later) environment.</td>
</tr>
<tr>
<td>Inputs – Sound Source</td>
<td>User selects the file containing a point based sound source location.</td>
<td>Same</td>
</tr>
<tr>
<td>Source Location</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Inputs – Model Extent</td>
<td>User specifies the modeling extent.</td>
<td>The modeling extent is specified in the ArcPy code. The tool clips the elevation</td>
</tr>
<tr>
<td></td>
<td></td>
<td>dataset to a distance of 2.0 miles (in the 1m, 1.5m, and 10m versions) or 2.5 miles</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(in the 30m [100 ft] version).</td>
</tr>
<tr>
<td>Inputs – Sound Source</td>
<td>Sound source height is not considered by SPReAD-GIS.</td>
<td>User inputs the height of the sound source. The ArcPy code adds this offset to the</td>
</tr>
<tr>
<td>Height (ft.)</td>
<td></td>
<td>surface elevation at the sound source location</td>
</tr>
<tr>
<td>Inputs – Frequency (Hz)</td>
<td>User selects frequency from a dropdown list of predetermined options.</td>
<td>User inputs frequency as a numerical value. There is no restriction on the value.</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Inputs – Sound Level</td>
<td>User specifies the sound level of the source.</td>
<td>Same</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Inputs – Measurement</td>
<td>User specifies the distance from the source at which the sound level was measured.</td>
<td>Same</td>
</tr>
<tr>
<td>Distance (ft.)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Inputs – Elevation</td>
<td>User selects an elevation raster with a 100 ft. (30 m) cell size. (Typically, data</td>
<td>The Soundshed Analysis Toolbox contains four versions of the Soundshed Analysis Tool</td>
</tr>
<tr>
<td>Dataset</td>
<td>would be a Digital Elevation Model.)</td>
<td>designed to work with different elevation datasets.</td>
</tr>
</tbody>
</table>
selecting a tool the user determines the resolution (cell size) of their elevation raster and chooses appropriately from: 1.0 m, 1.5 m, 10 m, 30 m (100 ft.). This step allows the user to select from a variety of elevation datasets, such as LiDAR data (often 1.0 or 1.5 m resolution), DEM (often 10 m or 100 ft. resolution), or other inputs. This option allows for high resolution modeling, but recognizes that high-res data is not available for all study areas.

<p>| Inputs – Land Cover Dataset | User selects a land cover raster dataset. This dataset should also have a 100 ft. cell size. | Differences in land cover within the study area are not considered by the Soundshed Analysis Tool. The Soundshed Analysis - Variable Cover tool includes calculations for vegetation attenuation as described in Chapter 6. |
| Inputs – Air Temperature (F) | User specifies the ambient air temperature at the sound source location. | Same |
| Inputs – Relative Humidity (%) | User specifies the relative humidity at the sound source location. | Same |
| Inputs – Prevailing Wind Direction (deg) | | Upwind and downwind losses are not considered by the Soundshed Analysis Tool. |
| Inputs - Wind Speed (MPH) | | Upwind and downwind losses are not considered by the Soundshed Analysis Tool. |
| Inputs – Seasonal Conditions | | Upwind and downwind losses are not considered by the Soundshed Analysis Tool. |
| Inputs – Ambient | SPReAD-GiS calls this input “Ambient Sound Conditions Dataset.” The user specifies the | The Soundshed Analysis Tool calls this input “Ambient Sound Pressure Level (dBA)” The user |</p>
<table>
<thead>
<tr>
<th>Sound Conditions</th>
<th>location of an ambient sound conditions raster dataset created using SPReAD-GIS Tool #1.</th>
<th>specifies a single ambient SPL of the study area and the ArcPy code creates an ambient sound conditions raster for use in modeling. Note that as described in Chapter 6 the Soundshed Analysis-Variable Cover tool requires users to input an Ambient SPL raster. This allows the user to select a raster containing a single ambient SPL value for the entire study area, or to use a raster with a different SPL values corresponding to the vegetation zones.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Outputs</td>
<td>SPReAD-GIS creates two modeling output rasters: Sound Propagation (&quot;pr&quot;: soundshed at an ambient SPL of 0 dB), and Excess Sound Propagation (&quot;ex&quot;: soundshed heard over ambient SPL). A number of intermediate/temporary files are created during the modeling process, these are all overwritten during subsequent runs of the model.</td>
<td>Like SPReAD-GIS, modeling output rasters include: Sound Propagation (&quot;pr&quot;: soundshed at an ambient SPL of 0 dB), and Rise over Ambient (&quot;ra&quot;: soundshed heard over ambient SPL). A number of intermediate/temporary files are created during the modeling process, these are all overwritten during subsequent runs of the model. The Soundshed Analysis Tool also creates the following output rasters: Distance Attenuation (&quot;ss&quot;: spherical spreading losses), and Viewshed (&quot;vs&quot;).</td>
</tr>
</tbody>
</table>
Appendix B: Python Scripts

**Script 1:** Python Script for the Soundshed Analysis Tool “Soundshed_m.py”

(The remainder of this page has intentionally been left blank for formatting purposes.)
import sys, math, string, os, shutil, arcpy
from arcpy import env
from arcpy.sa import *

# Set the workspace environment setting
arcpy.env.overwriteOutput = True
arcpy.env.workspace = r'C:\SoundAnalysis\Data\Model_Output.gdb'

# Input parameters
Sound_Source = arcpy.GetParameterAsText(0)
Source_Height = arcpy.GetParameterAsText(1)
freq_s = arcpy.GetParameterAsText(2)
Sound_Level = arcpy.GetParameterAsText(3)
Measurement_Distance = arcpy.GetParameterAsText(4)
temp_s = arcpy.GetParameterAsText(5)
hum_s = arcpy.GetParameterAsText(6)
ambient_dba = arcpy.GetParameterAsText(7)
dem = arcpy.GetParameterAsText(8)
cell_size = arcpy.GetParameterAsText(9)
model_name = arcpy.GetParameterAsText(10)

arcpy.Delete_management(temp_folder)
arcpy.Delete_management(ambient)
arcpy.Delete_management(study_area)
arcpy.Delete_management(study_area_ft)
# Create temporary folder
folder_path = r"C:\SoundAnalysis"
folder_name = "temp"
arcpy.CreateFolder_management(folder_path, folder_name)

## Define a Study Area ##

# Add notification message
arcpy.AddMessage("Defining the study area ...")

# Set spatial reference
dscRD2 = arcpy.Describe(dem)
sr = dscRD2.SpatialReference
arcpy.env.outputCoordinateSystem = sr

# Define a 2 mile study area around the sound source
buffs = r"C:\SoundAnalysis\temp\StudyArea_Buf.shp"
arcpy.Buffer_analysis(Sound_Source, buffs, "2.0 Miles", "FULL", "ROUND", "LIST")

# Rasterize study area
buff_ras = r"C:\SoundAnalysis\temp\StudyArea_Buf"
resolution = float(cell_size)
arcpy.FeatureToRaster_conversion(buffs, "Id", buff_ras, resolution)

# Clip the input dem to the 2 mi study area
study_area_temp = r"C:\SoundAnalysis\temp\StudyArea_dem"
arcpy.Clip_management(dem, ",", study_area_temp, buff_ras, ",", "NONE", "," "NO_MAINTAIN_EXTENT"")

# Copy intermediate data to preliminary results
study_area = r"C:\SoundAnalysis\Data\Model_Output.gdb\StudyArea_dem"
arcpy.CopyRaster_management(study_area_temp, study_area)

# Set general parameters for rasters
dscRD = arcpy.Describe(study_area)
RasterExtent = dscRD.Extent
CellSize = dscRD.MeanCellHeight
arcpy.env.snapRaster = study_area

# Set Environment settings
arcpy.env.extent = RasterExtent
arcpy.env.cellSize = CellSize
arcpy.env.snapRaster = arcpy.Raster(study_area)

# Add notification message
arcpy.AddMessage("Creating ambient dBA dataset ...")

# Create constant raster of ambient dBA
ambient_temp = r"C:\SoundAnalysis\temp\ambient"
ambient_float = float(ambient_dba)
outConstRaster = CreateConstantRaster(ambient_float, "FLOAT", CellSize, RasterExtent)
outConstRaster.save(ambient_temp)

# Copy intermediate data to preliminary results
ambient = r"C:\SoundAnalysis\Data\Model_Output.gdb\AmbientDb"
arcpy.CopyRaster_management(ambient_temp, ambient)

# Convert elevation values from meters to feet
ambient = r"C:\SoundAnalysis\temp\StudyArea_ft"
outTimes = Times(study_area, 3.2808)
outTimes.save(elev)

# Copy intermediate data to preliminary results
study_area_ft = r"C:\SoundAnalysis\Data\Model_Output.gdb\StudyArea_ft"
arcpy.CopyRaster_management(elev, study_area_ft)

## CALCULATE DISTANCE ATTENUATION ##

# Add notification message
arcpy.AddMessage("Calculating distance attenuation ...")

# Local variables
eucdist_ft = r"C:\SoundAnalysis\temp\eucdist_ft"
eucdist = r"C:\SoundAnalysis\temp\eucdist"
eucdir = r"C:\SoundAnalysis\temp\eucdir"
source_elv = r"C:\SoundAnalysis\temp\source_elv"
sound_src = r"C:\SoundAnalysis\temp\sound_src"
sound_elv = r"C:\SoundAnalysis\temp\sound_elv.shp"

# Extract elevation value to sound source point
ExtractValuesToPoints(Sound_Source, elev, sound_elv, "NONE", "VALUE_ONLY")

# Add offset height in feet for viewshed calculation
height = float(Source_Height)
arcpy.AddField_management(Sound_Source, "OFFSETA", "SHORT")
arcpy.CalculateField_management(Sound_Source, "OFFSETA", height, "VB")

# Convert sound source to raster dataset
arcpy.PointToRaster_conversion(sound_elv, "RASTERVALU", source_elv, "", "", resolution)

# Adding sound source height to ground elevation
outPlus = Plus(source_elv, height)
outPlus.save(sound_src)

# Calculate Euclidean allocation, distance, and direction around sound source
outEucDirect = EucDirection(sound_src, "", resolution, eucdist)
outEucDirect.save(eucdir)

# Convert Euclidean distance from meters to feet
outTimes = Times(eucdist, 3.2808)
outTimes.save(eucdist_ft)

# Divide Euclidean distance by measurement distance (X/y)
xy_grid = r"C:\SoundAnalysis\temp\xy_grid"
measdist_ft = float(Measurement_Distance)
outDivide = Divide(eucdist_ft, measdist_ft)
outDivide.save(xy_grid)

# Calculate distance attenuation
ssl_neg = r"C:\SoundAnalysis\temp\ssl_neg"
outRas = (20 * (Log10(xy_grid))) * -1
outRas.save(ssl_neg)

# Create constant raster of source sound level at specified frequency
source_dba = r"C:\SoundAnalysis\temp\source" + freq_s
outConstRaster = CreateConstantRaster(Sound_Level, "FLOAT", CellSize, RasterExtent)
outConstRaster.save(source_dba)

# Subtract distance attenuation from source sound level
ssl_temp = r"C:\SoundAnalysis\temp\ssl" + freq_s
outPlus = Plus(ssl_neg, source_dba)
outPlus.save(ssl_temp)

# Copy intermediate data to preliminary results
ssl = r"C:\SoundAnalysis\Data\Model_Output.gdb\ssl" + freq_s
 arcpy.CopyRaster_management(ssl_temp, ssl)

## CALCULATE ATMOSPHERIC ABSORPTION LOSS ##

# Convert input parameters to numbers
rh = float(hum_s)
temp_f = float(temp_s)
freq = float(freq_s)

# Identify ground elevation at sound source
elev_value = r"C:\SoundAnalysis\temp\elev_value.dbf"
Sample(elev, sound_src, elev_value, "BILINEAR")
cursor = arcpy.SearchCursor(elev_value)
row = cursor.next()

while row:
    elev_const = row.getValue("StudyArea_")
    row = cursor.next()

# Add the height of sound source to the ground elevation at the sound source
source_elevation = elev_const + height

# Update message
elev_s = str(source_elevation)
eleva = float(source_elevation)
arcpy.AddMessage("Calculating atmospheric absorption loss for an elevation of " +
elev_s + " ft, air temperature of " + temp_s + " degrees, and " + hum_s + "% humidity ...")

# Calculate atmospheric absorption coefficient using ANSI standard
# Convert temperature from Fahrenheit to Kelvins
204  temp_c = (temp_f - 32) * 5 / 9
205  temp_k = temp_c + 273.15
206
207  # Convert elevation to atmospheric pressure
208  elev_m = eleva / 3.28084
209  p_a = 101.325 * (1 - 2.25577 * 10 ** (-5) * elev_m) ** 5.25588
210
211  # Convert relative humidity to molar concentration of water vapor
212  C = (-6.8346 * (273.16 / temp_k) ** 1.261) + 4.6151
213  psat_pr = 10 ** C
214
215  # Calculate values for subsequent equations
216  alpha = 101.325 * (p_a / 101.325) ** (-1)
217
218  # Calculate frO (equation 3)
219  frO = pa_pr * (24 + (((4.04 * (10 ** 4) * h) * (0.02 + h)) / (0.391 + h)))
220
221  # Calculate frN (equation 4)
222  frN = pa_pr * (T_Tr ** (-0.5)) * (9 + (280 * h) * (e ** (-4.170 * ((T_Tr ** (-0.33333)) - 1))))
223
224  # Calculate alpha (equation 5)
225  term1 = 1.84 * (10 ** (-11)) * (pa_pr ** (-1)) * (T_Tr ** 0.5)
226  term2 = (T_Tr ** (-2.5)) * (0.01275 * (e ** (-2239.1 / temp_k)) * (frO / ((frO ** 2) + (freq ** 2))))
227  term3 = 0.1068 * (e ** (-3352 / temp_k)) * (frN / ((frN ** 2) + (freq ** 2))))
228  alpha = 8.686 * (freq ** 2) * (term1 + term2 + term3)
229  alpha_ft = alpha / 3.28084
230
231  # Create constant raster of atmospheric absorption coefficient
232  aac = r"C:\SoundAnalysis\Temp\aac" + freq_s
233  outConstRaster = CreateConstantRaster(alpha_ft, "FLOAT", CellSize, RasterExtent)
234  outConstRaster.save(aac)
235
236  # Calculate atmospheric absorption loss
237  aaloss = r"C:\SoundAnalysis\Temp\aal" + freq_s
238  outTimes = Times(eucdist_ft, aac)
239  outTimes.save(aaloss)
240
241  # Calculate cumulative distance attenuation and atmospheric absorption loss
242  sslaal_temp = r"C:\SoundAnalysis\Temp\sslaal" + freq_s
243  outMinus = Minus(ssl_temp, aaloss)
244  outMinus.save(sslaal_temp)
245
246  ## CALCULATE VIEWSHED, TOPOGRAPHIC EFFECTS AND BARRIER LOSS ##
247
248  # Environment settings
249  arcpy.env.extent = RasterExtent
250  arcpy.env.cellSize = CellSize
251
252  # Raster Extent
253  arcpy.env.extent = RasterExtent
254  arcpy.env.cellSize = CellSize
255
256  # VIEWSHED
257  soundAnalysis = CreateVIEWSHED() # FUTURE:
258  soundAnalysis.run(RasterExtent, RasterExtent, RasterExtent, RasterExtent, RasterExtent, RasterExtent)
259
260  # TOPOGRAPHIC EFFECTS
261  topoEffect = CreateTOPOGRAPHICEffect() # FUTURE:
262  topoEffect.run(RasterExtent, RasterExtent, RasterExtent, RasterExtent, RasterExtent, RasterExtent)
263
264  # BARRIER LOSS
265  barrierLoss = CreateBARRIERLoss() # FUTURE:
266  barrierLoss.run(RasterExtent, RasterExtent, RasterExtent, RasterExtent, RasterExtent, RasterExtent)
267
268  # Accumulate all effects
269  allEffects = Minus(ssl_temp, aaloss)
270  allEffects.save(allEffects)
271
272  # Combine VIEWSHED, TOPOGRAPHIC EFFECTS and BARRIER LOSS
273  totalEffects = Minus(allEffects, sslaal_temp)
274  totalEffects.save(totalEffects)
275
276  # Calculate final attenuation
277  finalAttenuation = Minus(allEffects, totalEffects)
278  finalAttenuation.save(finalAttenuation)
279
280  # Export final results
281  arcpy.env.extent = RasterExtent
282  arcpy.env.cellSize = CellSize
283  finalResults.save(results)
284
285  # HTTPS://example.com/attenuation
286  # HTTPS://example.com/finalResults
287  # HTTPS://example.com/results
# Update message
arcpy.AddMessage("Identifying barrier effects ...")

# Delineate basins
flow_dir = r"C:\SoundAnalysis\temp\flow_dir"
all_basins = r"C:\SoundAnalysis\temp\all_basins"
outFlowDirection = FlowDirection(elev)
outFlowDirection.save(flow_dir)
outBasin = Basin(flow_dir)
outBasin.save(all_basins)

# Identify sound source basin
sound_src_basin = r"C:\SoundAnalysis\temp\sound_src_basin.dbf"
basin = r"C:\SoundAnalysis\temp\basin"
Sample(all_basins, sound_src, sound_src_basin, "BILINEAR")
cursor = arcpy.SearchCursor(sound_src_basin)
row = cursor.next()
while row:
    basin_num = row.getValue("all_basins")
    row = cursor.next()
arcpy.gp.ExtractByAttributes_sa(all_basins, "VALUE = " + str(basin_num), basin)

# Delineate barrier (ie, ridgeline) around sound source basin
basin_exp = r"C:\SoundAnalysis\temp\basin_exp"
basin_shr = r"C:\SoundAnalysis\temp\basin_shr"
outExpand = Expand(basin, 1, basin_num)
outExpand.save(basin_exp)
outShrink = Shrink(basin_exp, 1, basin_num)
outShrink.save(basin_shr)
basin_shr_rc = r"C:\SoundAnalysis\temp\basin_shr_rc"
barrier = r"C:\SoundAnalysis\temp\barrier"
basin_plus1 = basin_num + 1
outReclass = Reclassify(basin_shr, "VALUE", RemapValue([[basin_num, "NODATA"],["NODATA", basin_plus1]]))
outReclass.save(basin_shr_rc)
outMinus = Minus(basin_shr_rc, basin_exp)
outMinus.save(barrier)

# Define areas where ground effects dominate
ground = r"C:\SoundAnalysis\temp\ground"
outReclass = Reclassify(basin_exp, "VALUE", RemapValue([[basin_num, 3],["NODATA", 0]]))
outReclass.save(ground)

# Calculate viewshed for source point
viewshed = r"C:\SoundAnalysis\temp\viewshed"
outViewshed = Viewshed(elev, Sound_Source, 0.3048)
outViewshed.save(viewshed)

# Copy intermediate data to preliminary results
view = r"C:\SoundAnalysis\Data\Model_Output.gdb\viewshed"
arcpy.CopyRaster_management(viewshed, view)

# Define areas where ground effects and atmospheric effects dominate
ground_atmos = r"C:\SoundAnalysis\temp\ground_atmos"
outCellStats = CellStatistics([ground, viewshed], "MAXIMUM", "DATA")
outCellStats.save(ground_atmos)

# Define areas where ground, atmospheric, and barrier effects dominate
topo_zones = r"C:\SoundAnalysis\temp\topo_zones"
outReclass = Reclassify(ground_atmos, "VALUE", RemapValue([[0,2],"NODATA",2]))
outReclass.save(topo_zones)

# Update message
arcpy.AddMessage("Calculating decline in sound levels due to barrier loss ...")

# Sample Euclidean direction, elevation, and Euclidean distance values along barrier
sample = r"C:\SoundAnalysis\temp\sample.dbf"
elev_dist_mean = r"C:\SoundAnalysis\temp\elev_dist_mean.dbf"
Sample([eucdir, elev, eucdist_ft], barrier, sample, "BILINEAR")
arcpy.Statistics_analysis(sample, elev_dist_mean, ["StudyArea_", "mean"], ["eucdist_ft", "min"])
arcpy.AddField_management(elev_dist_mean, "elev", "SHORT")
arcpy.AddField_management(elev_dist_mean, "dist", "SHORT")
arcpy.CalculateField_management(elev_dist_mean, "elev", "[mean_Study]"

# Assign barrier elevation value by Euclidean direction
elev_barrier = r"C:\SoundAnalysis\temp\elev_barrier"
outRaster = ReclassByTable(eucdir, elev_dist_mean, "eucdir", "eucdir", "elev", "NODATA")
outRaster.save(elev_barrier)
EucAllocate = EucAllocation(elev_barrier)
EucAllocate.save(elev_barrier)

# Assign barrier distance value by Euclidean direction
dist_barrier = r"C:\SoundAnalysis\temp\dist_barrier"
dist_barrier = r"C:\SoundAnalysis\temp\dist_barrier"
outRaster = ReclassByTable(eucdir, elev_dist_mean, "eucdir", "eucdir", "dist", "NODATA")
outRaster.save(dist_barrier)
EucAllocate = Euc Allocation (dist_barrier)
EucAllocate.save(dist_barrier)

# Make constant raster of sound source elevation
elev_source = r"C:\SoundAnalysis\temp\elev_source"
arcpy.env.outputCoordinateSystem = elev
outConstRaster = CreateConstantRaster(source_elevation, "FLOAT", CellSize, elev)
outConstRaster.save(elev_source)

# Calculate slope between source and receiver
slope = r"C:\SoundAnalysis\temp\slope"
outRas = (Raster(elev) - Raster(elev_source)) / Raster(eucdist_ft)
outRas.save(slope)

# Calculate elevation of source-receiver line under barrier
elev_sr = r"C:\SoundAnalysis\temp\elev_sr"
outRas = (Raster(slope) * Raster(dist_barrier)) + Raster(elev_source)
outRas.save(elev_sr)

# Calculate barrier height
h_b = r"C:\SoundAnalysis\temp\h_b"
outRas = Raster(elev_barrier) - Raster(elev_sr)
outRas.save(h_b)

# Reclassify negative barrier height values to zero
h_b_rc = r"C:\SoundAnalysis\temp\h_b_rc"
arcpy.gp.Reclassify_sa(h_b, "VALUE", "-10000 0 0", h_b_rc, "DATA")

# Calculate barrier path distance (BPD)
bar_pathdist = r"C:\SoundAnalysis\temp\bar_pathdist"
outRas = SquareRoot(Square(Raster(h_b_rc)) + Square(Raster(dist_barrier))) +
SquareRoot(Square(Raster(h_b_rc)) + Square((Raster(eucdist_ft) -
Raster(dist_barrier)))) - Raster(eucdist_ft)
outRas.save(bar_pathdist)

# Calculate barrier factor (fresnel number)
bar_factor = r"C:\SoundAnalysis\temp\bar_factor"
freq = float(freq_s)
wavelength = 1126.038 / freq
fresnel = 2 / wavelength
outTimes = Times(bar_pathdist, fresnel)
outTimes.save(bar_factor)

# Calculate barrier effect loss
bar_loss = r"C:\SoundAnalysis\temp\bar" + freq_s
pi = float(math.pi)
outRas = 20 * Log10((SquareRoot(2 * (pi * Raster(bar_factor))))/(TanH(SquareRoot(2 *
(pi * Raster(bar_factor)))))) + 5
outRas.save(bar_loss)

# Calculate cumulative distance attenuation, atmospheric absorption, and barrier
effect loss
ssl_br = r"C:\SoundAnalysis\temp\sslbr" + freq_s
outMinus = Minus(sslaal_temp, bar_loss)
outMinus.save(ssl_br)

# Pick noise propagation values for areas where ground, atmospheric, or barrier
effects dominate
sslbrtp_temp = r"C:\SoundAnalysis\temp\sslbrtp" + freq_s
outPick = Pick(topo_zones, [sslaal_temp, ssl_br, sslalal_temp])
```python
outPick.save(sslbrtp_temp)

## CALCULATE SUMMARY NOISE PROPAGATION PATTERNS ##

# Update message
arcpy.AddMessage("Calculating final noise propagation patterns and rise over ambient dBA ...")

# Smooth noise propagation patterns
smooth = r"C:\SoundAnalysis\temp\smooth" + freq_s
outFocalStat = FocalStatistics(sslbrtp_temp, NbrRectangle(3, 3, "CELL"), "MEAN", "DATA")
outFocalStat.save(smooth)

# Patch to prevent smoothing at cell of origin
pr_file = r"C:\SoundAnalysis\temp\pr.tif"
outCon = Con((sound_src > 0), sslbrtp_temp, smooth)
outCon.save(pr_file)

# Remove propagation values that are less than zero
OutRasterA = r"C:\SoundAnalysis\temp\pr" + freq_s
outCon = Con(Raster(pr_file) > 0, Raster(pr_file), 0)
outCon.save(OutRasterA)

#remove No Data values from output
OutRasterB = r"C:\SoundAnalysis\temp\pr_data" + freq_s
outCon = Con(IsNull(Raster(OutRasterA)), 0, Raster(OutRasterA))
outCon.save(OutRasterB)

# Copy intermediate data to preliminary results
pr_data = r"C:\SoundAnalysis\Data\Model_Output.gdb\pr_data" + freq_s
arcpy.CopyRaster_management(OutRasterB, pr_data)

# Subtract ambient conditions from propagation values to calculate rise over ambient dBA
OutRasterC = r"C:\SoundAnalysis\temp\ex" + freq_s
outCon = Con(Raster(OutRasterB) > Raster(ambient), Raster(OutRasterB) - Raster(ambient), 0)
outCon.save(OutRasterC)

# Copy excess noise propagation data to results geodatabase
ex_data = r"C:\SoundAnalysis\Data\Model_Output.gdb\ex" + freq_s
arcpy.CopyRaster_management(OutRasterC, ex_data)

#Define Variables to Rename Sound Propagation and Rise over Ambient Outputs
in_rename = str(model_name)
out_rename_pr = r"C:\SoundAnalysis\Data\Model_Output.gdb\pr_" + in_rename
out_rename_ex = r"C:\SoundAnalysis\Data\Model_Output.gdb\ra_" + in_rename
out_rename_ssl = r"C:\SoundAnalysis\Data\Model_Output.gdb\ss_" + in_rename
out_rename_view = r"C:\SoundAnalysis\Data\Model_Output.gdb\vs_" + in_rename

# Execute Rename of Sound Propagation
arcpy.Rename_management(pr_data, out_rename_pr)
```
Execute Rename of Rise over Ambient

```
arcpy.Rename_management(ex_data, out_rename_ex)
```

Execute Rename of Distance Attenuation

```
arcpy.Rename_management(ssl, out_rename_ssl)
```

Execute Rename of Viewshed

```
arcpy.Rename_management(view, out_rename_view)
```

Compact the Geodatabase

```
gdb_name = r"C:\SoundAnalysis\Data\Model_Output.gdb"
arcpy.Compact_management(gdb_name)
```
**Script 2:** Python Script for the Soundshed Analysis Tool “Soundshed_mVEG.py”

(The remainder of this page has intentionally been left blank for formatting purposes.)
# Soundshed_mVEG.py
# Author: Kristy E. Primeau
# Version 0.9.3
# Version Date: 4 December 2021
# Adapted from "SPreAD GIS" by Sarah E. Reed
# Description: Calculates decline in sound level due to distance attenuation, atmospheric effects, barrier effects, and vegetation attenuation; summarizes noise propagation patterns
# Requirements: Spatial Analyst Extension
# Python Reference: I wonder where that fish could be, for it went where I did go.

# Import system modules
import sys, math, string, os, shutil, arcpy
from arcpy import env
from arcpy.sa import *

# Delete intermediate datasets, if they exist
env.overwriteOutput = True

# Set the workplace environment setting
env.workspace = r"C:\SoundAnalysis\Data\Model_Output.gdb"

# Input parameters
Sound_Source = arcpy.GetParameterAsText(0)
Source_Height = arcpy.GetParameterAsText(1)
freq_s = arcpy.GetParameterAsText(2)
Sound_Level = arcpy.GetParameterAsText(3)
Measurement_Distance = arcpy.GetParameterAsText(4)
temp_s = arcpy.GetParameterAsText(5)
hum_s = arcpy.GetParameterAsText(6)
ambient_dba = arcpy.GetParameterAsText(7)
veg = arcpy.GetParameterAsText(8)
dem = arcpy.GetParameterAsText(9)
cell_size = arcpy.GetParameterAsText(10)
model_name = arcpy.GetParameterAsText(11)

# Issue warning that data from prior model runs will be deleted
arcpy.AddWarning("Warning: Data from prior runs of the Soundshed model will be deleted and results for the " + freq_s + " Hz frequency band will be overwritten ...")

## Delete any pre-existing layers (overwrite should take care of this, but it hasn't been working in 10.7)
temp_folder = r"C:\SoundAnalysis\temp"
ambient = r"C:\SoundAnalysis\Data\Model_Output.gdb\AmbientDba"
study_area = r"C:\SoundAnalysis\Data\Model_Output.gdb\StudyArea_dem"
study_area_ft = r"C:\SoundAnalysis\Data\Model_Output.gdb\StudyArea_ft"
arcpy.Delete_management(temp_folder)
arcpy.Delete_management(ambient)
arcpy.Delete_management(study_area)
arcpy.Delete_management(study_area_ft)

# Create temporary folder
folder_path = r"C:\SoundAnalysis"
folder_name = "temp"
arcpy.CreateFolder_management(folder_path, folder_name)

## Define a Study Area ##

# Add notification message
arcpy.AddMessage("Defining the study area ...")

# Set spatial reference
dscRD2 = arcpy.Describe(dem)
sr = dscRD2.SpatialReference
arcpy.env.outputCoordinateSystem = sr

# Define a 2.0 mile study area around the sound source
buffs = r"C:\SoundAnalysis\temp\StudyArea_Buf.shp"
arcpy.Buffer_analysis(Sound_Source, buffs, "2.0 Miles", "FULL", "ROUND", "LIST")

# Rasterize study area
buff_ras = r"C:\SoundAnalysis\temp\StudyArea_Buf"
resolution = float(cell_size)
arcpy.FeatureToRaster_conversion(buffs, "Id", buff_ras, resolution)

# Clip the input dem to the 2.0 mi study area
study_area_temp = r"C:\SoundAnalysis\temp\StudyArea_dem"
arcpy.Clip_management(dem, "#", study_area_temp, buff_ras, "#", "NONE", "MAINTAIN_EXTENT")

# Copy intermediate data to preliminary results
study_area = r"C:\SoundAnalysis\Data\Model_Output.gdb\StudyArea_dem"
arcpy.CopyRaster_management(study_area_temp, study_area)

# Set general parameters for rasters
dscRD = arcpy.Describe(study_area)
RasterExtent = dscRD.Extent
CellSize = dscRD.MeanCellHeight
arcpy.env.snapRaster = study_area

# Set Environment settings
arcpy.env.extent = RasterExtent
arcpy.env.cellSize = CellSize
arcpy.env.snapRaster = arcpy.Raster(study_area)

# Convert elevation values from meters to feet
dem_ft = r"C:\SoundAnalysis\temp\StudyArea_ft"
outTimes = Times(study_area, 3.2808)
outTimes.save(dem_ft)  # the study area in feet
# Copy intermediate data to preliminary results
study_area_ft = r"C:\SoundAnalysis\Data\Model_Output.gdb\StudyArea_ft"
arcpy.CopyRaster_management(dem_ft, study_area_ft)

### CALCULATE DISTANCE ATTENUATION ###

# Add notification message
arcpy.AddMessage("Calculating distance attenuation ...")

# Local variables
eucdist_ft = r"C:\SoundAnalysis\temp\eucdist_ft"
eucdist = r"C:\SoundAnalysis\temp\eucdist"
eucdir = r"C:\SoundAnalysis\temp\eucdir"
source_elv = r"C:\SoundAnalysis\temp\source_elv"
sound_src = r"C:\SoundAnalysis\temp\source_elv.shp"
sound_prof = r"C:\SoundAnalysis\temp\sound_prof"

# Extract elevation value to sound source point
ExtractValuesToPoints(Sound_Source, dem_ft, sound_elv, "NONE", "VALUE_ONLY")

# Add offset height in feet for viewshed calculation
height = float(Source_Height)
arcpy.AddField_management(Sound_Source, "OFFSETA", "SHORT")
arcpy.CalculateField_management(Sound_Source, "OFFSETA", height, "VB")

# Convert sound source to raster dataset
arcpy.PointToRaster_conversion(sound_elv, "RASTERVALU", source_elv, "", "", resolution)

# Adding sound source height to ground elevation
outPlus = Plus(source_elv, height)
outPlus.save(sound_src)

# Calculate Euclidean allocation, distance, and direction around sound source
outEucDirect = EucDirection(sound_src, "", resolution, eucdist)
outEucDirect.save(eucdir)

# Convert Euclidean distance from meters to feet
outTimes = Times(eucdist, 3.2808)
outTimes.save(eucdist_ft)

# Divide Euclidean distance by measurement distance (X/y)
xy_grid = r"C:\SoundAnalysis\temp\xy_grid"
measdist_ft = float(Measurement_Distance)
outDivide = Divide(eucdist_ft, measdist_ft)
outDivide.save(xy_grid)

# Calculate distance attenuation
ssl_neg = r"C:\SoundAnalysis\temp\ssl_neg"
outRas = (20 * (Log10(xy_grid))) * -1
outRas.save(ssl_neg)

# Create constant raster of source sound level at specified frequency
source_dba = r"C:\SoundAnalysis\temp\source" + freq_s
outConstRaster = CreateConstantRaster(Sound_Level, "FLOAT", CellSize, RasterExtent)
outConstRaster.save(source_dba)

# Subtract distance attenuation from source sound level
ssl_temp = r"C:\SoundAnalysis\temp\ssl" + freq_s
outPlus = Plus(ssl_neg, source_dba)
outPlus.save(ssl_temp)

# Copy intermediate data to preliminary results
ssl = r"C:\SoundAnalysis\Data\Model_Output.gdb\ssl" + freq_s
arcpy.CopyRaster_management(ssl_temp, ssl)

## CALCULATE ATMOSPHERIC ABSORPTION ##

# Convert input parameters to numbers
rh = float(hum_s)
temp_f = float(temp_s)
freq = float(freq_s)

de = Source提炼声音源

delev_value = r"C:\SoundAnalysis\temp\elev_value.dbf"
Sample(dem_ft, sound_src, elev_value, "BILINEAR")
cursor = arcpy.SearchCursor(elev_value)
row = cursor.next()

while row:
    elev_const = row.getValue("StudyArea_")
    row = cursor.next()

# Add the height of sound source to the ground elevation at the sound source
source_elevation = elev_const + height

# Update message
elev_s = str(source_elevation)
eleva = float(source_elevation)
arcpy.AddMessage("Calculating atmospheric absorption loss for an elevation of " + elev_s + " ft, air temperature of " + temp_s + " degrees, and " + rh + "% humidity ...")

# Convert elevation to atmospheric pressure
elev_m = eleva / 3.28084
p_a = 101.325 * (1 - 2.25577 * 10 ** (-5) * elev_m) ** 5.25588

# Convert relative humidity to molar concentration of water vapor
C = (-6.8346 * (273.16 / temp_k) ** 1.261) + 4.6151
psat_pr = 10 ** C
h = rh * psat_pr * (p_a / 101.325) ** (-1)

# Calculate derived values for subsequent equations
pa_pr = p_a / 101.325
T_Tr = temp_k / 293.15
e = 2.7182818284

# Calculate frO (equation 3)
frO = pa_pr * (24 + ((( 4.04 * (10 ** 4) * h) * (0.02 + h)) / (0.391 + h)))

# Calculate frN (equation 4)
frN = pa_pr * (T_Tr ** (-0.5)) * (9 + (280 * h) * (e ** (-4.170 * ((T_Tr ** (-0.33333)) - 1))))

# Calculate alpha (equation 5)
term1 = 1.84 * (10 ** (-11)) * (pa_pr ** (-1)) * (T_Tr ** 0.5)
term2 = (T_Tr ** (-2.5)) * (0.01275 * (e ** (-2239.1 / temp_k)))*frO / ((frO ** 2) + (freq ** 2)))
term3 = 0.1068 * (e ** (-3352 / temp_k)) * (frN / ((frN ** 2) + (freq ** 2)))
alpha = 8.686 * (freq ** 2)*(term1 + term2 + term3)
alpha_ft = alpha / 3.28084

# Create constant raster of atmospheric absorption coefficient
aac = r'C:\SoundAnalysis\temp\aac' + freq_s
outConstRaster = CreateConstantRaster(alpha_ft, "FLOAT", CellSize, RasterExtent)
outConstRaster.save(aac)

# Calculate atmospheric absorption loss
aaloss = r'C:\SoundAnalysis\temp\aal' + freq_s
outTimes = Times(eucdist_ft, aac)
outTimes.save(aaloss)

# Calculate cumulative distance attenuation and atmospheric absorption loss
sslaal_temp = r'C:\SoundAnalysis\temp\sslaal' + freq_s
outMinus = Minus(ssl_temp, aaloss)
outMinus.save(sslaal_temp)

## CALCULATE FOLIAGE & GROUND COVER LOSS ##

arcpy.AddMessage("Calculating land cover impedance ...")

# Environment settings
env.extent = RasterExtent
env.cellSize = CellSize

# Create a constant raster of value = 1
constant1 = r'C:\SoundAnalysis\temp\constant1'
outConstRaster = CreateConstantRaster("1", "INTEGER", CellSize, RasterExtent)
outConstRaster.save(constant1)

# Take maximum value of the Euclidean distance grid
eucdist_max = r'C:\SoundAnalysis\temp\eucdist_max'
outZonalStatistics = ZonalStatistics(constant1, "VALUE", eucdist_ft,"MAXIMUM", 359
outZonalStatistics.save(eucdist_max)

# Subtract maximum distance from the Euclidean distance grid and take its absolute value

eucdist_z = r"C:\SoundAnalysis\temp\eucdist_z"
outAbs = Abs(Raster(eucdist_ft) - Raster(eucdist_max))
outAbs.save(eucdist_z)

# Clip the input dem to the 2.0 mi study area

veg_clip = r"C:\SoundAnalysis\temp\veg_clip"
arcpy.Clip_management(veg, "#", veg_clip, study_area, "#", "NONE", "MAINTAIN_EXTENT")

# Reclassify land cover datasets by foliage and ground cover loss rates

veg_lossrate = r"C:\SoundAnalysis\temp\veg_lossrate"
outReclass = Reclassify(veg_clip, "VEGTYPE", RemapValue(["A", 0], ["B", 101], ["C", 501], ["D", 662]), "DATA")
outReclass.save(veg_lossrate)

# Buffer sound source point (to reduce errors in path distance calculations)

sound_src_veg = r"C:\SoundAnalysis\temp\sound_src_veg.shp"
arcpy.Buffer_analysis(Sound_Source, sound_src_veg, "%s Meters" % CellSize, "FULL", "ROUND", "ALL")

# Calculate the cost raster for vegetation loss by distance

scale_factor = CellSize * 3.28084
outRas = ((Raster(veg_lossrate)/Raster(eucdist_ft))/scale_factor) + 1
outRas.save(veg_cost)

# Calculate path distance around buffered source point (without vegetation loss)

pathdist1 = r"C:\SoundAnalysis\temp\pathdist1"
outPathDist = PathDistance(sound_src_veg, "", eucdist_z, "", HfBinary(1, 45), "", VfBinary(1, -30, 30), ")
outPathDist.save(pathdist1)

# Calculate path distance around buffered source point (with vegetation loss)

pathdist2 = r"C:\SoundAnalysis\temp\pathdist2"
outPathDist = PathDistance(sound_src_veg, veg_cost, eucdist_z, "", "BINARY 1 45", "", "BINARY 1 -30 30")
outPathDist.save(pathdist2)

# Subtract path distance 1 from path distance 2 to calculate vegetation loss

veg_pre = r"C:\SoundAnalysis\temp\veg_pre" + freq_s + ".tif"
outMinus = Minus(pathdist2, pathdist1)
outMinus.save(veg_pre)

# Prevent an inaccurate assessment at the origin cell

vegras = r"C:\SoundAnalysis\temp\vegras" + freq_s

veg = Con(IsNull(veg_pre), 0, veg_pre)
veg.save(vegras)
# Calculate cumulative spherical spreading, atmospheric absorption, and vegetation loss

```python
salveg_temp = r"C:\SoundAnalysis\temp\salveg" + freq_s
goMinus = Minus(sslal_temp, vegras)
outMinus.save(salveg_temp)
```

## CALCULATE VIEWSHED, TOPOGRAPHIC EFFECTS AND BARRIER LOSS ##

# Update message
arcpy.AddMessage("Identifying barrier effects ...")

# Delineate basins
```python
flow_dir = r"C:\SoundAnalysis\temp\flow_dir"
all_basins = r"C:\SoundAnalysis\temp\all_basins"
```

# Identify sound source basin
```python
sound_src_basin = r"C:\SoundAnalysis\temp\sound_src_basin.dbf"
basin = r"C:\SoundAnalysis\temp\basin"
```

# Delineate barrier (ie, ridgeline) around sound source basin
```python
basin_exp = r"C:\SoundAnalysis\temp\basin_exp"
basin_shr = r"C:\SoundAnalysis\temp\basin_shr"
```

# Define areas where ground effects dominate
```python
ground = r"C:\SoundAnalysis\temp\ground"
```
outReclass = Reclassify(basin_exp, "VALUE", RemapValue([[basin_num, 3],["NODATA", 0]]))
outReclass.save(ground)

# Calculate viewshed for source point
viewshed = r"C:\SoundAnalysis\temp\viewshed"
outViewshed = Viewshed(dem_ft, Sound_Source, 0.3048)
outViewshed.save(viewshed)

# Copy intermediate data to preliminary results
view = r"C:\SoundAnalysis\Data\Model_Output.gdb\viewshed"
arcpy.CopyRaster_management(viewshed, view)

# Define areas where ground effects and atmospheric effects dominate
ground_atmos = r"C:\SoundAnalysis\temp\ground_atmos"
outCellStats = CellStatistics([ground, viewshed], "MAXIMUM", "DATA")
outCellStats.save(ground_atmos)

# Define areas where ground, atmospheric, and barrier effects dominate
topo_zones = r"C:\SoundAnalysis\temp\topo_zones"
outReclass = Reclassify(ground_atmos, "VALUE", RemapValue([[0,2],["NODATA",2]]))
outReclass.save(topo_zones)

# Define areas where ground effects and atmospheric effects dominate
ground_atmos = r"C:\SoundAnalysis\temp\ground_atmos"
outCellStats = CellStatistics([ground, viewshed], "MAXIMUM", "DATA")
outCellStats.save(ground_atmos)

# Define areas where ground, atmospheric, and barrier effects dominate
topo_zones = r"C:\SoundAnalysis\temp\topo_zones"
outReclass = Reclassify(ground_atmos, "VALUE", RemapValue([[0,2],["NODATA",2]]))
outReclass.save(topo_zones)

# Update message
arcpy.AddMessage("Calculating decline in sound levels due to barrier loss ...")

# Sample Euclidean direction, elevation, and Euclidean distance values along barrier
sample = r"C:\SoundAnalysis\temp\sample.dbf"
elev_dist_mean = r"C:\SoundAnalysis\temp\elev_dist_mean.dbf"
Sample([eucdir, dem_ft, eucdist_ft], barrier, sample, "BILINEAR")
arcpy.Statistics_analysis(sample, elev_dist_mean, [["StudyArea_", "mean"], ["eucdist_ft", "min"]], "eucdir")
arcpy.AddField_management(elev_dist_mean, "dem_ft", "SHORT")
arcpy.AddField_management(elev_dist_mean, "dist", "SHORT")
arcpy.CalculateField_management(elev_dist_mean, "eucdir", "[mean_Study]"")
arcpy.CalculateField_management(elev_dist_mean, "dist", "[min_eucdis]"")

# Assign barrier elevation value by Euclidean direction
elev_bar_dir = r"C:\SoundAnalysis\temp\elev_bar_dir"
elev_barrier = r"C:\SoundAnalysis\temp\elev_barrier"
outRaster = ReclassByTable(eucdir, elev_dist_mean, "eucdir", "eucdir", "dem_ft", "NODATA")
outRaster.save(elev_bar_dir)
EucAllocate = EucAllocation(elev_bar_dir)
EucAllocate.save(elev_barrier)

# Assign barrier distance value by Euclidean direction
dist_bar_dir = r"C:\SoundAnalysis\temp\dist_bar_dir"
dist_barrier = r"C:\SoundAnalysis\temp\dist_barrier"
outRaster = ReclassByTable(eucdir, elev_dist_mean, "eucdir", "eucdir", "dist", "NODATA")
outRaster.save(dist_bar_dir)
EucAllocate = EucAllocation(dist_bar_dir)
EucAllocate.save(dist_barrier)

# Make constant raster of sound source elevation

elev_source = r"C:\SoundAnalysis\temp\elev_source"

arcpy.env.outputCoordinateSystem = dem_ft
outConstRaster = CreateConstantRaster(source_elevation, "FLOAT", CellSize, dem_ft)
outConstRaster.save(elev_source)

# Calculate slope between source and receiver

slope = r"C:\SoundAnalysis\temp\slope"
outRas = (Raster(dem_ft) - Raster(elev_source)) / Raster(eucdist_ft)
outRas.save(slope)

elev_sr = r"C:\SoundAnalysis\temp\elev_sr"
outRas = (Raster(slope) * Raster(dist_barrier)) + Raster(elev_source)
outRas.save(elev_sr)

# Calculate barrier height

h_b = r"C:\SoundAnalysis\temp\h_b"
outRas = Raster(elev_barrier) - Raster(elev_sr)
outRas.save(h_b)

# Reclassify negative barrier height values to zero

h_b_rc = r"C:\SoundAnalysis\temp\h_b_rc"
arcpy.gp.Reclassify_sa(h_b, "VALUE", "-10000 0 0", h_b_rc, "DATA")

# Calculate barrier path distance (BPD)

bar_pathdist = r"C:\SoundAnalysis\temp\bar_pathdist"
outRas = SquareRoot(Square(Raster(h_b_rc)) + Square(Raster(dist_barrier)) ) +
SquareRoot(Square(Raster(h_b_rc)) + Square((Raster(eucdist_ft) -
Raster(dist_barrier))) - Raster(eucdist_ft))
outRas.save(bar_pathdist)

# Calculate barrier factor (fresnel number)

freq = float(freq_s)
wavelength = 1126.038 / freq
fresnel = 2 / wavelength
outTimes = Times(bar_pathdist, fresnel)
outTimes.save(bar_factor)

# Calculate barrier effect loss

bar_loss = r"C:\SoundAnalysis\temp\bar" + freq_s
pi = float(math.pi)
outRas = 20 * Log10((SquareRoot(2 * (pi * Raster(bar_factor))))/(TanH(SquareRoot(2 *
(pi * Raster(bar_factor))))) ) + 5
outRas.save(bar_loss)

# Calculate cumulative distance attenuation, atmospheric absorption, vegetation, and
barrier effect loss

ssl_br = r"C:\SoundAnalysis\temp\sslbr" + freq_s
outMinus = Minus(salveg_temp, bar_loss)
outMinus.save(ssl_br)

# Pick noise propagation values for areas where ground, atmospheric, vegetation, or barrier effects dominate
sslbrtp_temp = r"C:\SoundAnalysis\temp\sslbrtp" + freq_s
outPick = Pick(topo_zones, [sslaal_temp, ssl_br, salveg_temp])
outPick.save(sslbrtp_temp)

## CALCULATE SUMMARY NOISE PROPAGATION PATTERNS ##

# Update message
arcpy.AddMessage("Calculating final noise propagation patterns and rise over ambient dBA ...")

# Smooth noise propagation patterns
smoothed_file = r"C:\SoundAnalysis\temp\smth.tif"
smoothed = FocalStatistics(sslbrtp_temp, "Rectangle 3 3 CELL", "MEAN", "DATA")
smoothed.save(smoothed_file)

# Patch to prevent smoothing at cell of origin
pr_file = r"C:\SoundAnalysis\temp\pr.tif"
outCon = Con((sound_src > 0), sslbrtp_temp, smoothed_file)
outCon.save(pr_file)

# Remove propagation values that are less than zero
OutRasterA = r"C:\SoundAnalysis\temp\pr" + freq_s
outCon = Con(Raster(pr_file) > 0, Raster(pr_file), 0)
outCon.save (OutRasterA)

#remove No Data values from output
pr_temp = r"C:\SoundAnalysis\temp\pr_data" + freq_s
outCon = Con(IsNull(Raster(OutRasterA)), 0, Raster(OutRasterA))
outCon.save(pr_temp)

# Copy intermediate data to preliminary results
pr_data = r"C:\SoundAnalysis\Data\Model_Output.gdb\pr_data" + freq_s
arcpy.CopyRaster_management(pr_temp, pr_data)

# Subtract ambient conditions from propagation values to calculate rise over ambient dBA
ex_temp = r"C:\SoundAnalysis\temp\ex" + freq_s
outCon = Con(Raster(pr_temp) > Raster(ambient_dba), Raster(pr_temp) - Raster(ambient_dba), 0)
outCon.save(ex_temp)

# Copy excess noise propagation data to results geodatabase
excess = r"C:\SoundAnalysis\Data\Model_Output.gdb\ex" + freq_s
arcpy.CopyRaster_management(ex_temp, excess)

# Define Variables to Rename Sound Propagation and Rise over Ambient Outputs
in_rename = str(model_name)
out_rename_pr = r"C:\SoundAnalysis\Data\Model_Output.gdb\pr_" + in_rename
out_rename_ex = r"C:\SoundAnalysis\Data\Model_Output.gdb\ra_" + in_rename
out_rename_ssl = r"C:\SoundAnalysis\Data\Model_Output.gdb\ss_" + in_rename
out_rename_view = r"C:\SoundAnalysis\Data\Model_Output.gdb\vs_" + in_rename

# Execute Rename of Sound Propagation
arcpy.Rename_management(pr_data, out_rename_pr)

# Execute Rename of Rise over Ambient
arcpy.Rename_management(excess, out_rename_ex)

# Execute Rename of Distance Attenuation
arcpy.Rename_management(ssl, out_rename_ssl)

# Execute Rename of Viewshed
arcpy.Rename_management(view, out_rename_view)

# Compact the Geodatabase

gdb_name = r"C:\SoundAnalysis\Data\Model_Output.gdb"

arcpy.Compact_management(gdb_name)
Appendix C: Variable Cover Tool Modeling Results

Figure C-1.1. Estimated soundshed of a shell horn played from the East Court (Point 1) at an Acropolis Procession during the reign of Ruler 13 [Created using the Variable Cover Tool at a Single Ambient dBA]
Figure C-1.2. Estimated soundshed of a shell horn played from the East Court (Point 1) at an Acropolis Procession during the reign of Ruler 13 [Created using the Variable Cover Tool at a Single Ambient dBA, shown with Land Cover Types]
**Figure C-1.3.** Estimated soundshed of a shell horn played from the East Court (Point 1) at an Acropolis Procession during the reign of Ruler 13 [Created using the Variable Cover Tool at a Variable Ambient dBA]
Figure C-1.4. Estimated soundshed of a shell horn played from the East Court (Point 1) at an Acropolis Procession during the reign of Ruler 13 [Created using the Variable Cover Tool at a Variable Ambient dBA, shown with Land Cover Types]
Figure C-2.1. Estimated soundshed of a shell horn played from the East Court (Point 7) at an Acropolis Procession during the reign of Ruler 13 [Created using the Variable Cover Tool at a Single Ambient dBA]
**Figure C-2.2.** Estimated soundshed of a shell horn played from the East Court (Point 7) at an Acropolis Procession during the reign of Ruler 13 [Created using the Variable Cover Tool at a Single Ambient dBA, shown with Land Cover Types]
**Figure C-2.3.** Estimated soundshed of a shell horn played from the East Court (Point 7) at an Acropolis Procession during the reign of Ruler 13 [Created using the Variable Cover Tool at a Variable Ambient dBA]
Figure C-2.4. Estimated soundshed of a shell horn played from the East Court (Point 7) at an Acropolis Procession during the reign of Ruler 13 [Created using the Variable Cover Tool at a Variable Ambient dBA, shown with Land Cover Types]
Appendix D: Chaco Canyon Modeling Results

**Figure D-1.1.** Estimated Soundshed of Crowds at Various Locations within Chaco Canyon at Dawn on the Summer Solstice
Figure D-1.2. Estimated Soundshed of Crowds at Various Locations within Chaco Canyon at Noon on the Summer Solstice
Figure D-2.1. Estimated Soundshed of an Elite Orator Speaking from Pueblo Alto at Dawn on the Summer Solstice
Figure D-2.2. Estimated Soundshed of an Elite Orator Speaking from Kin Kletso at Dawn on the Summer Solstice
Figure D-2.3. Estimated Soundshed of an Elite Orator Speaking from the Triwall Feature at Pueblo del Arroyo at Dawn on the Summer Solstice.
Figure D-2.4. Estimated Soundshed of an Elite Orator Speaking from the Courtyard at Pueblo del Arroyo at Dawn on the Summer Solstice
Figure D-2.5. Estimated Soundshed of an Elite Orator Speaking from Inside the West Plaza\(^1\) of Pueblo Bonito at Dawn on the Summer Solstice

This is the location of the Ponderosa pine tree, which is estimated to have been approximately 100 years old prior to the construction of Pueblo Bonito (Stein et al. 2007:204).
Figure D-2.6. Estimated Soundsheid of an Elite Orator Speaking from the Platform Mounds at Pueblo Bonito at Dawn on the Summer Solstice
Figure D-2.7. Estimated Soundshed of an Elite Orator Speaking from Behind the Back Wall of Pueblo Bonito at Dawn on the Summer Solstice
Figure D-2.8. Estimated Soundshed of an Elite Orator Speaking from the Colonnade at Chetro Ketl at Dawn on the Summer Solstice
Figure D-2.9. Estimated Soundshed of an Elite Orator Speaking from Chetro Ketl at Dawn on the Summer Solstice
Figure D-2.10. Estimated Soundshed of an Elite Orator Speaking from Casa Rincoña at Dawn on the Summer Solstice
Figure D-2.11. Estimated Soundshed of an Elite Orator Speaking from Hungo Pavi at Dawn on the Summer Solstice
Figure D-3.1. Estimated Soundshed of an Elite Orator Speaking from Penasco Blanco at Noon on the Summer Solstice
Figure D-3.2. Estimated Soundshed of an Elite Orator Speaking from Casa Chiquita at Noon on the Summer Solstice
Figure D-3.3. Estimated Soundshed of an Elite Orator Speaking from Kin Kletso at Noon on the Summer Solstice
Figure D-3.4. Estimated Soundshed of an Elite Orator Speaking from the Courtyard at Pueblo del Arroyo at Noon on the Summer Solstice
Figure D-3.5. Estimated Soundshed of an Elite Orator Speaking from Inside the West Plaza of Pueblo Bonito at Noon on the Summer Solstice
Figure D-3.6. Estimated Soundshed of an Elite Orator Speaking from the Colonnade at Chetro Ketl at Noon on the Summer Solstice
Figure D-3.7. Estimated Soundshed of an Elite Orator Speaking from Casa Rincoñada at Noon on the Summer Solstice
Figure D-3.8. Estimated Soundshed of an Elite Orator Speaking from Hungo Pavi at Noon on the Summer Solstice
Figure D-3.9. Estimated Soundshed of an Elite Orator Speaking from Kin Nahasbas at Noon on the Summer Solstice
Figure D-3.10. Estimated Soundshed of an Elite Orator Speaking from Una Vida at Noon on the Summer Solstice
**Figure D-3.11.** Estimated Soundshed of an Elite Orator Speaking from Wijiji at Noon on the Summer Solstice
Figure D-3.12. Estimated Soundshed of an Elite Orator Speaking from Shrine 29SJ1207 at Noon on the Summer Solstice
**Figure D-3.13.** Estimated Soundshed of an Elite Orator Speaking from Shrine 29SJ2384 at Noon on the Summer Solstice
Figure D-3.14. Estimated Soundshed of an Elite Orator Speaking from Shrine 29SJ2420 at Noon on the Summer Solstice
Figure D-3.15. Estimated Soundshed of an Elite Orator Speaking from Shrine 29SJ423 at Noon on the Summer Solstice
Figure D-3.16. Estimated Soundshed of an Elite Orator Speaking from Shrine 29SJ706 at Noon on the Summer Solstice
Figure D-3.17. Estimated Soundshed of an Elite Orator Speaking from Stone Circle 29SJ1326 at Noon on the Summer Solstice
Figure D-3.18. Estimated Soundshed of an Elite Orator Speaking from Stone Circle 29SJ1419 at Noon on the Summer Solstice
Figure D-3.19. Estimated Soundshed of an Elite Orator Speaking from Stone Circle 29SJ1474 at Noon on the Summer Solstice
Figure D-3.20. Estimated Soundshed of an Elite Orator Speaking from Stone Circle 29SJ1505E at Noon on the Summer Solstice
Figure D-3.21. Estimated Soundshed of an Elite Orator Speaking from Stone Circle 29SJ1533 at Noon on the Summer Solstice
Figure D-3.22. Estimated Soundshed of an Elite Orator Speaking from Stone Circle 29SJ1565 at Noon on the Summer Solstice
Figure D-3.23. Estimated Soundshed of an Elite Orator Speaking from Stone Circle 29SJ1572 at Noon on the Summer Solstice
Figure D-3.24. Estimated Soundshed of an Elite Orator Speaking from Stone Circle 29SJ1660 at Noon on the Summer Solstice
Figure D-3.25. Estimated Soundshed of an Elite Orator Speaking from Stone Circle 29SJ1976A_F at Noon on the Summer Solstice
Figure D-3.26. Estimated Soundshed of an Elite Orator Speaking from Stone Circle 29SJ2240 at Noon on the Summer Solstice
Figure D-3.27. Estimated Soundshed of an Elite Orator Speaking from Stone Circle 29SJ866 at Noon on the Summer Solstice
Figure D-3.28. Estimated Soundshed of an Elite Orator Speaking from Stone Circle 29SJ919 at Noon on the Summer Solstice
Figure D-3.29. Estimated Soundshed of an Elite Orator Speaking from Stone Circle LA40692_N at Noon on the Summer Solstice
Figure D-3.30. Estimated Soundshed of an Elite Orator Speaking from Stone Circle LA40692_S at Noon on the Summer Solstice
Figure D-4.1. Estimated Soundshed of a Conch Shell Trumpet Played from Pueblo Alto at Dawn on the Summer Solstice
Figure D-4.2. Estimated Soundshed of a Conch Shell Trumpet Played from Kin Kletso at Dawn on the Summer Solstice
Figure D-4.3. Estimated Soundshed of a Conch Shell Trumpet Played from the Triwall Feature at Pueblo del Arroyo at Dawn on the Summer Solstice
Figure D-4.4. Estimated Soundshed of a Conch Shell Trumpet Played from the Courtyard at Pueblo del Arroyo at Dawn on the Summer Solstice
Figure D-4.5. Estimated Soundshed of a Conch Shell Trumpet Played from Inside the West Plaza of Pueblo Bonito at Dawn on the Summer Solstice
Figure D-4.6. Estimated Soundshed of a Conch Shell Trumpet Played from Inside the West Plaza of Pueblo Bonito at Dawn on the Summer Solstice
Figure D-4.7. Estimated Soundshed of a Conch Shell Trumpet Played from the Colonnade at Chetro Ketl at Dawn on the Summer Solstice.
Figure D-4.8. Estimated Soundshed of a Conch Shell Trumpet Played from Chetro Ketl at Dawn on the Summer Solstice
**Figure D-4.9.** Estimated Soundshed of a Conch Shell Trumpet Played from Hungo Pavi at Dawn on the Summer Solstice
**Figure D-5.1.** Estimated Soundshed of a Conch Shell Trumpet Played from Pueblo Alto at Noon on the Summer Solstice
Figure D-5.2. Estimated Soundshed of a Conch Shell Trumpet Played from Kin Kletso at Noon on the Summer Solstice
Figure D-5.3. Estimated Soundshed of a Conch Shell Trumpet Played from the Triwall Feature at Pueblo del Arroyo at Noon on the Summer Solstice
Figure D-5.4. Estimated Soundshed of a Conch Shell Trumpet Played from the Courtyard at Pueblo del Arroyo at Noon on the Summer Solstice
Figure D-5.5. Estimated Soundshed of a Conch Shell Trumpet Played from Inside the West Plaza of Pueblo Bonito at Noon on the Summer Solstice
Figure D-5.6. Estimated Soundshead of a Conch Shell Trumpet Played from the Platform Mounds at Pueblo Bonito at Noon on the Summer Solstice
Figure D-5.7. Estimated Soundshed of a Conch Shell Trumpet Played from Behind the Back Wall of Pueblo Bonito at Noon on the Summer Solstice
Figure D-5.8. Estimated Soundshed of a Conch Shell Trumpet Played from the Colonnade at Chetro Ketl at Noon on the Summer Solstice
Figure D-5.9. Estimated Soundshed of a Conch Shell Trumpet Played from Chetro Ketl at Noon on the Summer Solstice
Figure D-5.10. Estimated Soundshed of a Conch Shell Trumpet Played from Casa Rincoñada at Noon on the Summer Solstice
Figure D-5.11. Estimated Soundshed of a Conch Shell Trumpet Played from Hungo Pavi at Noon on the Summer Solstice
### Table D-1. Interaudibility of Site Locations within Chaco Canyon (Page 1 of 6)

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**Table D-1. Interaudibility of Site Locations within Chaco Canyon (Page 2 of 6)**

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### Table D-2. Interaudibility Connection Table

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**Key:**
- **SI** = Speech Likely Intelligible
- **A** = Actively Audible
- **L** = Likely Audible (based on interpretation)

Note that this table has been modified from the version used in ArcGIS to preserve the confidentiality of site location coordinates.
Appendix E: Copán Modeling Results

Figure E-1.1. Estimated soundshed of Ruler 13 speaking from Stela 4
Figure E-1.2. Estimated soundshed of Ruler 13 speaking from Stela A
Figure E-1.3. Estimated soundshed of Ruler 13 speaking from Stela B

Audibility of a Raised Voice at Stela B

Inputs
- Sound Source Height: 5 ft.
- Frequency: 225 Hz.
- Sound Level of Source: 85 dB
- Measurement Distance: 1 ft.
- Temperature: 79 F
- Relative Humidity: 90%
- Ambient SPL: 31 dB
- Elevations: Ruler 13

Legend
- Stela or Structure
- Audible Area (R.13)
- Structures

Sound Pressure Level (dB)
- High: 42.1744
- Low: 0

Elevation (m.a.s.l.)
- High: 911.083
- Low: 571.104
Figure E-1.4. Estimated soundshed of Ruler 13 speaking from Stela C
Figure E-1.5. Estimated soundshed of Ruler 13 speaking from Stela D
Figure E-1.6. Estimated soundshed of Ruler 13 speaking from Stela F
Figure E-1.7. Estimated soundshed of Ruler 13 speaking from Stela H
Figure E-1.8. Estimated soundshed of Ruler 13 speaking from Structure 10L-4
Figure E-2. Maximum soundshed extent of Ruler 13’s stelae circuit
Figure E-3.1. Audibility and Visibility of Ruler 13 while speaking from Stela 4

Inputs
- Sound Source Height: 5 ft.
- Frequency: 225 Hz.
- Sound Level of Source: 85 dB
- Measurement Distance: 1 ft.
- Temperature: 79 F
- Relative Humidity: 90%
- Ambient SPL: 31 dB
- Elevations: Ruler 13

Legend
- Stela or Structure
- Visible Area
- Audible Area (R.13)
- Structures

Sound Pressure Level (dB)
- High: 42.1744
- Low: 0

Elevation (m-asl)
- High: 911.083
- Low: 571.104

1:3,000
Figure E-3.2. Audibility and Visibility of Ruler 13 while speaking from Stela A

Audibility and Visibility Raised Voice at Stela A

Inputs
- Sound Source Height: 5 ft.
- Frequency: 225 Hz.
- Sound Level of Source: 85 dB
- Measurement Distance: 1 ft.
- Temperature: 79 F
- Relative Humidity: 90%
- Ambient SPL: 31 dB
- Elevations: Ruler 13

Legend
- Green Circle: Stele or Structure
- Blue Area: Visible Area
- Orange Area: Audible Area (R. 13)
- Structures
- Sound Pressure Level (dB)
  - High: 42.1744
  - Low: 0
- Elevation (m-ssl)
  - High: 911.083
  - Low: 571.104

1:3,000
Figure E-3.3. Audibility and Visibility of Ruler 13 while speaking from Stela B

Inputs
- Sound Source Height: 5 ft.
- Frequency: 225 Hz.
- Sound Level of Source: 85 dB
- Measurement Distance: 1 ft.
- Temperature: 79 F
- Relative Humidity: 90%
- Ambient SPL: 31 dB
- Elevations: Ruler 13

Legend
- Stela or Structure
- Visible Area
- Audible Area (R 13)
- Structures
- Sound Pressure Level (dB)
  - High: 42.1744
  - Low: 0
- Elevation (m-nsl)
  - High: 911.083
  - Low: 571.104

1:3,000
Figure E-3.4. Audibility and Visibility of Ruler 13 while speaking from Stela C
Figure E-3.5. Audibility and Visibility of Ruler 13 while speaking from Stela D
Figure E-3.6. Audibility and Visibility of Ruler 13 while speaking from Stela F
Figure E-3.7. Audibility and Visibility of Ruler 13 while speaking from Stela H

Audibility and Visibility Raised Voice at Stela H

Inputs
- Sound Source Height: 5 ft.
- Frequency: 225 Hz.
- Sound Level of Source: 85 dB
- Measurement Distance: 1 ft.
- Temperature: 79 F
- Relative Humidity: 90%
- Ambient SPL: 31 dB
- Elevations: Ruler 13

Legend
- Stela or Structure
- Visible Area
- Audible Area (R. 13)
- Structures
- Sound Pressure Level (dB)
  - High: 42.1744
  - Low: 0
- Elevation (m-ssl)
  - High: 911.083
  - Low: 571.104
Figure E-3.8. Audibility and Visibility of Ruler 13 while speaking from Structure 10L-4
Figure E-4.1. Estimated soundshed of a shell horn played from Point 1 at an Acropolis Procession during the reign of Ruler 13
Figure E-4.2. Estimated soundshed of a shell horn played from the West Court (Point 2) at an Acropolis Procession during the reign of Ruler 13.
Figure E-4.3. Estimated soundshed of a shell horn played from the West Court (Point 3) at an Acropolis Procession during the reign of Ruler 13
Figure E-4.4. Estimated soundshed of a shell horn played from the West Court (Point 4) at an Acropolis Procession during the reign of Ruler 13
Figure E-4.5. Estimated soundshed of a shell horn played from the West Court (Point 5) at an Acropolis Procession during the reign of Ruler 13
Figure E-4.6. Estimated soundshed of a shell horn played from the entrance to the East Court (Point 6) at an Acropolis Procession during the reign of Ruler13.
Figure E-4.7. Estimated soundshed of a shell horn played from the East Court (Point 7) at an Acropolis Procession during the reign of Ruler 13
**Figure E-4.8.** Estimated soundshed of a shell horn played from the East Court (Point 8) at an Acropolis Procession during the reign of Ruler 13
Figure E-4.9. Estimated soundshed of a shell horn played from the East Court (Point 9) at an Acropolis Procession during the reign of Ruler 13
Figure E-4.10. Estimated soundshed of a shell horn played from the East Court (Point 7) at an Acropolis Procession during the reign of Ruler 13
Figure E-4.11. Estimated soundshed of a shell horn played from the East Court (Point 11) at an Acropolis Procession during the reign of Ruler 13
**Figure E-4.12.** Estimated soundshed of a shell horn played from midway up the East Court's Jaguar stairway (Point 12) at an Acropolis Procession during the reign of Ruler 13.
Figure E-4.13. Estimated soundshed of a shell horn played atop the Jaguar dance Platform (Point 13) at an Acropolis Procession during the reign of Ruler 13.
Figure E-5. Maximum soundshed extent of a shell horn played at an Acropolis Procession during the reign of Ruler 13
Figure E-6.1. Audibility and Visibility of a shell horn player from Point 1 at an Acropolis Procession during the reign of Ruler 13
Figure E-6.2. Audibility and Visibility of a shell horn player from the West Court (Point 2) at an Acropolis Procession during the reign of Ruler 13
**Figure E-6.3.** Audibility and Visibility of a shell horn player from the West Court (Point3) at an Acropolis Procession during the reign of Ruler 13

**Inputs**
- Sound Source Height: 6 ft.
- Frequency: 330 Hz.
- Sound Level of Source: 96 dB
- Measurement Distance: 1 ft.
- Temperature: 79 F
- Relative Humidity: 90%
- Ambient SPL: 31 dB
- Elevations: Ruler 13

**Legend**
- Procession Waypoints
- Visible Area
- Audible Area (R. 13)
- Structures
- Sound Pressure Level (dB)
  - High: 53.1735
  - Low: 0
- Elevation (m-ssl)
  - High: 911.083
  - Low: 571.104

1:8,000

0 125 250 375 500

Metres
Figure E-6.4. Audibility and Visibility of a shell horn player from the West Court (Point 4) at an Acropolis Procession during the reign of Ruler 13
Figure E-6.5. Audibility and Visibility of a shell horn player from the West Court (Point 5) at an Acropolis Procession during the reign of Ruler 13
Figure E-6.6. Audibility and Visibility of a shell horn player from the entrance to the East Court (Point 6) at an Acropolis Procession during the reign of Ruler 13
Figure E-6.7. Audibility and Visibility of a shell horn player from the East Court (Point 7) at an Acropolis Procession during the reign of Ruler 13
Figure E-6.8. Audibility and Visibility of a shell horn player from the East Court (Point 8) at an Acropolis Procession during the reign of Ruler 13
Figure E-6.9. Audibility and Visibility of a shell horn player from the East Court (Point 9) at an Acropolis Procession during the reign of Ruler 13
Figure E-6.10. Audibility and Visibility of a shell horn player from the East Court (Point 10) at an Acropolis Procession during the reign of Ruler 13
Figure E-6.11. Audibility and Visibility of a shell horn player from the East Court (Point 11) at an Acropolis Procession during the reign of Ruler 13
Figure E-6.12. Audibility and Visibility of a shell horn player from midway up the East Court's Jaguar stairway (Point 12) at an Acropolis Procession during the reign of Ruler 13.
Figure E-6.13. Audibility and Visibility of a shell horn player atop the Jaguar dance Platform (Point 13) at an Acropolis Procession during the reign of Ruler 13
Figure E-7.1. Estimated soundshed of a shell horn played from Point 1 at an Acropolis Procession during the reign of Ruler 16.
Figure E-7.2. Estimated soundshed of a shell horn played from the West Court (Point 2) at an Acropolis Procession during the reign of Ruler 16.
Figure E-7.3. Estimated soundshed of a shell horn played from the West Court (Point 3) at an Acropolis Procession during the reign of Ruler 16
Figure E-7.4. Estimated soundshed of a shell horn played from the West Court (Point 4) at an Acropolis Procession during the reign of Ruler 16

Inputs
- Sound Source Height: 6ft.
- Frequency: 330 Hz.
- Sound Level of Source: 96 dB
- Measurement Distance: 1ft.
- Temperature: 79 F
- Relative Humidity: 90%
- Ambient SPL: 31dB
- Elevations: Ruler 16

Legend
- Procession Waypoints
- Audible Area (R.16)
- Structures
- Sound Pressure Level (dB)
  - High: 53.1735
  - Low: 0
- Elevation (m-ssl)
  - High: 911.083
  - Low: 571.104

Map scale: 1:8,000
Figure E-7.5. Estimated soundshed of a shell horn played from the West Court (Point 5) at an Acropolis Procession during the reign of Ruler 16.
Figure E-7.6. Estimated soundshed of a shell horn played from the entrance to the East Court (Point 6) at an Acropolis Procession during the reign of Ruler 16

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| Audible Area (R.16)           |
| Structures                    |
| Sound Pressure Level (dB)      |
| High: 53.1735                 |
| Low: 0                        |
| Elevation (m-ssel)            |
| High: 911.083                 |
| Low: 571.104                  |
**Figure E-7.7.** Estimated soundshed of a shell horn played from the East Court (Point 7) at an Acropolis Procession during the reign of Ruler 16.
Figure E-7.8. Estimated soundshed of a shell horn played from the East Court (Point 8) at an Acropolis Procession during the reign of Ruler 16.
Figure E-7.9. Estimated soundshed of a shell horn played from the East Court (Point 9) at an Acropolis Procession during the reign of Ruler 16.
Figure E-7.10. Estimated soundshed of a shell horn played from the East Court (Point 10) at an Acropolis Procession during the reign of Ruler 16
Figure E-7.11. Estimated soundshed of a shell horn played from the East Court (Point 11) at an Acropolis Procession during the reign of Ruler 16
Figure E-7.12. Estimated soundshed of a shell horn played from midway up the East Court’s Jaguar stairway (Point 12) at an Acropolis Procession during the reign of Ruler 16.
Figure E-7.13. Estimated soundshed of a shell horn played atop the Jaguar dance Platform (Point 13) at an Acropolis Procession during the reign of Ruler 16.
Figure E-8. Maximum soundshed extent of a shell horn played at an Acropolis Procession during the reign of Ruler 16
Figure E-9.1. Audibility and Visibility of a shell horn player from Point 1 at an Acropolis Procession during the reign of Ruler 16
Figure E-9.2. Audibility and Visibility of a shell horn player from the West Court (Point 2) at an Acropolis Procession during the reign of Ruler 16.
**Figure E-9.3.** Audibility and Visibility of a shell horn player from the West Court (Point3) at an Acropolis Procession during the reign of Ruler 16
Figure E-9.4. Audibility and Visibility of a shell horn player from the West Court (Point 4) at an Acropolis Procession during the reign of Ruler 16.
Figure E-9.5. Audibility and Visibility of a shell horn player from the West Court (Point 5) at an Acropolis Procession during the reign of Ruler 16
Figure E-9.6. Audibility and Visibility of a shell horn player from the entrance to the East Court (Point 6) at an Acropolis Procession during the reign of Ruler 16
Figure E-9.7. Audibility and Visibility of a shell horn player from the East Court (Point 7) at an Acropolis Procession during the reign of Ruler 16.
Figure E-9.8. Audibility and Visibility of a shell horn player from the East Court (Point 8) at an Acropolis Procession during the reign of Ruler 16
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Figure E-9.10. Audibility and Visibility of a shell horn player from the East Court (Point 10) at an Acropolis Procession during the reign of Ruler 16
Figure E-9.11. Audibility and Visibility of a shell horn player from the East Court (Point 11) at an Acropolis Procession during the reign of Ruler 16
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**Figure E-10.** Comparison of maximum soundshed extents of shell horns played at Acropolis Processions during the reigns of Ruler 13 and Ruler 16
Figure E-11.1. Comparison of the estimated soundshed extents of shell horns played from Point 1 at an Acropolis Procession during the reigns of Ruler 13 and Ruler 16.
**Figure E-11.2.** Comparison of the estimated soundshed extents of shell horns played from the West Court (Point 2) at an Acropolis Procession during the reigns of Ruler 13 and Ruler 16.
**Figure E-11.3.** Comparison of the estimated soundshed extents of shell horns played from the West Court (Point3) at an Acropolis Procession during the reigns of Ruler 13 and Ruler 16
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**Figure E-11.5.** Comparison of the estimated soundshed extents of shell horns played from the West Court (Point 5) at an Acropolis Procession during the reigns of Ruler 13 and Ruler 16.
**Figure E-11.6.** Comparison of the estimated soundshed extents of shell horns played from the entrance to the East Court (Point 6) at an Acropolis Procession during the reigns of Ruler 13 and Ruler 16.
Figure E-11.7. Comparison of the estimated soundshed extents of shell horns played from the East Court (Point 7) at an Acropolis Procession during the reigns of Ruler 13 and Ruler 16
**Figure E-11.8.** Comparison of the estimated soundshed extents of shell horns played from the East Court (Point 8) at an Acropolis Procession during the reigns of Ruler 13 and Ruler 16
**Figure E-11.9.** Comparison of the estimated soundshed extents of shell horns played from the East Court (Point 9) at an Acropolis Procession during the reigns of Ruler 13 and Ruler 16.
Figure E-11.10. Comparison of the estimated soundshed extents of shell horns played from the East Court (Point 10) at an Acropolis Procession during the reigns of Ruler 13 and Ruler 16.
**Figure E-11.11.** Comparison of the estimated soundshed extents of shell horns played from the East Court (Point 11) at an Acropolis Procession during the reigns of Ruler 13 and Ruler 16
**Figure E-11.12.** Comparison of the estimated soundshed extents of shell horns played from midway up the East Court’s Jaguar stairway (Point 12) at an Acropolis Procession during the reigns of Ruler 13 and Ruler 16
Figure E-11.13. Comparison of the estimated soundshed extents of shell horns played atop the Jaguar dance Platform (Point 13) in the Acropolis Processions during the reigns of Ruler 13 and Ruler 16
Figure E-12.1. Estimated soundshed of a shell horn played at Stela 10 created using the Soundshed Analysis Tool

<table>
<thead>
<tr>
<th>Audibility of a Conch Shell Trumpet Stela 10</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inputs</td>
</tr>
<tr>
<td>Sound Source Height: 6ft.</td>
</tr>
<tr>
<td>Frequency: 330 Hz.</td>
</tr>
<tr>
<td>Sound Level of Source: 96 dB</td>
</tr>
<tr>
<td>Measurement Distance: 1ft.</td>
</tr>
<tr>
<td>Temperature: 79 F</td>
</tr>
<tr>
<td>Relative Humidity: 90%</td>
</tr>
<tr>
<td>Ambient SPL: 31dB</td>
</tr>
<tr>
<td>Elevations: Ruler 16</td>
</tr>
</tbody>
</table>

**Legend**
- Stela or Structure
- Audible Area (R-16)
- Structures
- Sound Pressure Level (dB)
  - High: 53.1735
  - Low: 0
- Elevation (m-asl)
  - High: 911.083
  - Low: 571.104

1:10,000

Meters 0 125 250 375 500

529
Figure E-12.2. Estimated soundshed of a shell horn played at Stela 12 created using the Soundshed Analysis Tool.
Figure E-12.3. Estimated soundshed of shell horns played at Stelae 10 and 12 created using the Soundshed Analysis Tool
Figure E-13.1. Audibility and Visibility of a shell horn player at Stela 10 created using the Soundshed Analysis Tool.
**Figure E-13.2.** Audibility and Visibility of a shell horn player at Stela 12 created using the Soundshed Analysis Tool
**Figure E-13.3.** Audibility and Visibility of a shell horn player at Stela 12 created using the Soundshed Analysis Tool (1:20,000)
Figure E-14.1. Estimated soundshed of a shell horn played at Stela 10 created using the Soundshed Analysis – Variable Cover tool.
Figure E-14.2. Estimated soundshed of a shell horn played at Stela 12 created using the Soundshed Analysis – Variable Cover tool
Figure E-14.3. Estimated soundshed of shell horns played at Stelae 10 and 12 created using the Soundshed Analysis – Variable Cover tool.
Appendix F: Ireland Modeling Results

Figure F-1.1: Estimated soundshed of a man speaking at GA 042-042001

Soundscape Extent of a Male Speaking at Dusk on October 31st

Site: GA 042-042001
Type: Rath, Childrens Burial Ground

Inputs
- Sound Source Height: 5ft.
- Frequency: 325 Hz.
- Sound Level of Source: 55 dB
- Measurement Distance: 3ft.
- Temperature: 46.76 F
- Relative Humidity: 87.5%
- Ambient SPL: 23 dB

Legend
- Site Location (NMS)
- Sound Pressure Level (dB)
  - High: 29.7163
  - Low: 0
- Elevation (m-asl)
  - High: 57.833
  - Low: 10.646
Figure F-1.2: Estimated soundshed of a man speaking at GA 042-043001
Figure F-1.3: Estimated soundshed of a man speaking at GA 042-044001

Soundscape Extent of a Male Speaking at Dusk on October 31st

Site: GA 042-044001
Type: Ringfort - Cashel

Inputs
- Sound Source Height: 5 ft.
- Frequency: 325 Hz.
- Sound Level of Source: 55 dB
- Measurement Distance: 3 ft.
- Temperature: 46.76°F
- Relative Humidity: 87.5%
- Ambient SPL: 23 dB

Legend
- Site Location (NMS)
- Sound Pressure Level (dB)
  - High: 29.7163
  - Low: 0
- Elevation (m-asl)
  - High: 87.833
  - Low: 10.646
Figure F-1.4: Estimated soundshed of a man speaking at GA 042-057

Soundscape Extent of a Male Speaking at Dusk on October 31st

Site: GA 042-057
Type: Ringfort - Cashel

Inputs
- Sound Source Height: 5 ft.
- Frequency: 325 Hz.
- Sound Level of Source: 55 dB
- Measurement Distance: 3 ft.
- Temperature: 46.76 F
- Relative Humidity: 87.5%
- Ambient SPL: 23 dB

Legend
- Site Location (NMS)
- Sound Pressure Level (dB)
  - High: 29.7163
  - Low: 0
- Elevation (m-asl)
  - High: 57.833
  - Low: 10.646
Figure F-1.5: Estimated soundshed of a man speaking at GA 042-058
Figure F-1.6: Estimated soundshed of a man speaking at GA 042-134
Figure F-2.1: Estimated soundshed of a man speaking at GA 042-042001 shown concurrently with the estimated soundshed of a man speaking at NIAH 30404212
Appendix G: Soundshed Analysis Toolbox User Manual

The Archaeoacoustics Toolbox is intended to be used by archaeologists and anthropologists wishing to gain a better understanding of what was heard in the past. While it does not necessarily require a background in acoustics, some basic understanding of sound physics is helpful for understanding the way that sound propagates and is quantified.

The Archaeoacoustics Toolbox contains two tools consisting of geometric-type models which assume sound travels through the air along straight-line paths. Directionality of the source and wave effects, such as reverberation, are not considered by the models. Both tools compute the soundshed for a single point study location. The tools use formulae of outdoor sound propagation, calculating free-field sound attenuation following ISO 9613-2 (ISO 1996), atmospheric absorption loss following ANSI 1.26 (ANSI 1995), topographic loss following ISO 9613-2 (ISO 1996), and barrier effects based on Maekawa’s optical diffraction theory (Lamancusa 2009; Maekawa 1968). In addition, the Soundshed Analysis – Variable Cover tool calculates vegetation loss following Aylor (1972) and SPReAD (Harrison et al. 1980; Reed et al. 2009, 2010). Raster outputs include Sound Propagation, Distance Attenuation, Viewshed, and Rise over Ambient Sound Pressure Level (dB).

The toolbox is intended for use in ESRI’s ArcGIS 10.3 or a later version. Users must have access to the Spatial Analyst extension and possess an Advanced license for
the toolbox to function properly. Python must also be installed on the windows computer (this is typically done during a standard ArcGIS installation). At a minimum, the elevation dataset used in modeling must cover the area within a 4.0 kilometer (2.5 mile) radius from the sound source location. The modeling resolution is determined by the cell size of the elevation raster dataset forming the basis of analysis, and can range from 1.0 m to 30.48 m (or 100 ft.).

The Archaeoacoustics Toolbox files are contained within the zipped folder named “SoundAnalysis.” This folder should be unzipped and placed in the C: drive of a windows computer. The folder contains 4 subfolders: Data, Scripts, temp, and Toolbox. The “Data” folder contains an empty ArcGIS geodatabase named “Model_Output.gdb.” The Python code used by the Soundsedh Analysis toolbox requires that both the “temp” folder and the geodatabase “Model_Output.gdb” remain in these locations using the precise naming and capitalization conventions appearing within the quotation marks for the tools to function correctly.

To add the Soundsedh Analysis toolbox to ArcGIS, open ArcMap. From the “Geoprocessing” menu select “ArcToolbox.” When the ArcToolbox window opens right click on the heading “ArcToolbox” and select “Add Toolbox.” When the Add Toolbox window opens use the “Look in:” dropdown menu to navigate to the following:

-------------------

1 The Archaeoacoustics Toolbox is made available on an “as is” basis, I make no representations or warranties, express or implied. Installation of the Archaeoacoustics Toolbox indicates an agreement of the terms of the GNU General Public License Version 3 or later versions http://www.gnu.org/licenses/gpl-3.0.txt.
C:\SoundAnalysis\Toolbox\Soundsched.tbx then click “Open” to add the toolbox. Archaeoacoustics Tools v0.9.3 will now appear in the ArcToolbox window. Double clicking the name of the tool will open its user interface. Prior to using the tools, read the descriptions provided below and select the appropriate tool for modeling based on the characteristics of your study area and hypothesis. Gather the required input data prior to modeling. If new datasets must be created (e.g. a shapefile or feature class containing the sound source location) ensure that they all use the same spatial projection. Best practice is to determine the projection and cell resolution of your elevation dataset and use that consistently for all modeling layers.

**Soundsched Analysis Tool**

The Soundsched Analysis Tool models how sound spreads throughout a landscape and is based upon “SPreAD” and “SPreAD-GIS” (Harrison et al. 1980; Reed et al. 2009, 2010). This tool assumes a constant ambient Sound Pressure Level (SPL) throughout the entire study area, and is best suited for modeling in open homogenous terrain, such as desert, plains, cleared agricultural land, or other areas where vegetation generally does not break the line of sight. Inputs for the Soundsched Analysis Tool are described below:

1. Sound source location: Select a shapefile or feature class containing a single sound source point location. Points used for modeling must be located in outdoor areas; enclosed or semi-enclosed areas will impact modeling results.
2. **Sound source height (ft):** Enter the height of the sound source in Feet measured between ground surface and the primary location where sound is produced (e.g. the bell of a trumpet, the mouth of a speaker). This information can be derived from osteological data, literature reviews, or from measurements taken while playing the instrument.
3. Frequency (Hz): Enter the dominant frequency of the sound source in Hertz. Inputs 3, 4, and 5 may be derived from literature reviews, or from measurements taken while playing the instrument.

4. Sound level of source (dBA): Enter the sound pressure level of the sound source in A-weighted decibels. Inputs 3, 4, and 5 may be derived from literature reviews, or from measurements taken while playing the instrument. If the instrument or sound producing device is a feature (e.g. rock gong) and measurements must be taken in the field, care must be taken to try to record measurements on a clear quiet day. Wind and other background noise can impact acoustical data.

5. Measurement Distance (ft.): Enter the distance between sound source and the location where the sound level was measured in feet. Note that Inputs 3, 4, and 5 must share a source as the nature of these inputs are inextricably connected. Either they are all published in the same reference material (e.g. within a single article or chapter), or they are measured contemporaneously in the field.

6. Temperature (F): Enter the air temperature in degrees Fahrenheit for your modeling scenario. This input is user defined based on a particular research hypothesis and should be connected to the source material used for Input 7. It may be gathered from historical records if such records exist, or derived from modern data (either in the field or through meteorological literature searches) and corrected manually to account for climate changes over time.
7. Relative Humidity (%): Enter the percentage of relative humidity for your modeling scenario. This input is user defined based on a particular research hypothesis and should be connected to the source material and subjected to the same correction factors used for Input 6.

8. Ambient sound pressure level (dBA): Enter the ambient or background sound pressure level in A-weighted decibels for your study area. This input may be derived from literature reviews, or from measurements taken in the field. Although this information may be collected independently of other inputs, if the measurements must be taken in the field, care must be taken to try to record measurements on a clear quiet day. Wind and other background noise can impact acoustical data.

9. Elevation Dataset: Select an elevation raster dataset (e.g. DEM, LiDAR) for your study area. At a minimum, the elevation dataset used in modeling must cover the area within a 4.0 kilometer (2.5 mile) radius from the sound source location.

10. Elevation Dataset Resolution (m): Choose the resolution of your elevation raster dataset. The resolution is based on the cell size of your dataset. To determine the cell size open ArcMap and add your elevation dataset to the map. Right click on the name of the elevation dataset in the Table of Contents, then select "Properties" at the bottom of the menu to open the Layer Properties window. Cell size is listed on the "Source" tab. If your dataset's cell size is not included in the standard options, select the next size larger.
11. Model Name (up to 9 characters): Choose a short name or nickname unique to this model run. Names must not exceed nine characters in length and cannot include a space. The underscore character is allowed. Note that if this model name has been used before, data from previous modeling runs completed with the same name will be overwritten or the tool may fail to function.

**Soundshed Analysis – Variable Cover Tool**

Soundshed Analysis – Variable Cover Tool calculates attenuation due to variable land-cover types, in addition barrier attenuation and atmospheric absorbance. It is best suited for modeling in areas of diverse ecotones. The Soundshed Analysis - Variable Cover Tool also includes the optional assignment of multiple ambient SPLs which can be based on cover type. It is also possible to use the Variable Cover Tool to model pockets of differing ambient SPLs in areas of open terrain (e.g. higher ambient SPL areas near a stream on a plain). Cover type categories are based on breaks in the line of sight between the sound source and receiver's position. Inputs for the Soundshed Analysis – Variable Cover Tool are described below:

1. Sound source location: Select a shapefile or feature class containing a single sound source point location. Points used for modeling must be located in outdoor areas; enclosed or semi-enclosed areas will impact modeling results.

2. Sound source height (ft): Enter the height of the sound source in Feet measured between ground surface and the primary location where sound is produced (e.g. 551
the bell of a trumpet, the mouth of a speaker). This information can be derived from osteological data, literature reviews, or from measurements taken while playing the instrument.

**Figure G.2.** Soundshed Analysis – Variable Cover Tool 0.9.3 Graphical User Interface

3. **Frequency (Hz):** Enter the dominant frequency of the sound source in Hertz. Inputs 3, 4, and 5 may be derived from literature reviews, or from measurements taken while playing the instrument.

4. **Sound level of source (dBA):** Enter the sound pressure level of the sound source in A-weighted decibels. Inputs 3, 4, and 5 may be derived from literature reviews,
or from measurements taken while playing the instrument. If the instrument or sound producing device is a feature (e.g. rock gong) and measurements must be taken in the field, care must be taken to try to record measurements on a clear quiet day. Wind and other background noise can impact acoustical data.

5. Measurement Distance (ft.): Enter the distance between sound source and the location where the sound level was measured in feet. Note that Inputs 3, 4, and 5 must share a source as the nature of these inputs are inextricably connected. Either they are all published in the same reference material (e.g. within a single article or chapter), or they are measured contemporaneously in the field.

6. Temperature (F): Enter the air temperature in degrees Fahrenheit for your modeling scenario. This input is user defined based on a particular research hypothesis and should be connected to the source material used for Input 7. It may be gathered from historical records if such records exist, or derived from modern data (either in the field or through meteorological literature searches) and corrected manually to account for climate changes over time.

7. Relative Humidity (%): Enter the percentage of relative humidity for your modeling scenario. This input is user defined based on a particular research hypothesis and should be connected to the source material and subjected to the same correction factors used for Input 6.

8. Ambient Sound Pressure Dataset: Select a raster containing the ambient sound pressure dataset. This dataset can be created two ways:
a. For a single ambient throughout the study area, the standard ArcGIS tool “Create Constant Raster” should be used. The “Constant Value” should be set to the ambient SPL, and the spatial projection and “Output Cell Size” should match the resolution of the elevation dataset which will be used for modeling. Optionally, the output extent can be set to the output extent of the elevation dataset.

b. In a landscape where the ambient varies, the user should first create a Polygon feature class using the same spatial projection as the elevation dataset which will be used for modeling, and divide up the study area into polygons accordingly. The feature class must include an attribute field named “VALUE” containing the ambient SPL for each polygon as an integer value. As an example, polygons may represent different vegetative cover types. The Polygon layer is then converted to a raster dataset using the standard ArcGIS tool “Feature to Raster” and specifying “VALUE” as the conversion “Field.”

9. Vegetative Cover Type: Select a raster containing the vegetative cover type dataset. This dataset can also be created two ways:

   a. If the polygons created for the Ambient Sound Pressure layer are based on vegetative cover types (i.e. the area and locations of the polygons within the two datasets are spatially identical) then the user can add an attribute field named “VEGTYPE” to the existing raster. Each polygon would be assigned a vegetation type A-D using the categories as described below. In this case,
the same raster dataset would be specified for both dropdown box locations (“Ambient Sound Pressure Dataset” and “Vegetative Cover Type”) in the Soundshe’d Analysis – Variable Cover tool graphical user interface.

b. If a single (constant) ambient dataset is being used or if the ambient and cover type datasets are not spatially identical, the user should first create a Polygon feature class using the same spatial projection as the elevation dataset which will be used for modeling, and divide up the study area into polygons accordingly. The feature class must include an attribute field named “VEGTYPE” containing the vegetation type A-D using the categories as described below. The Polygon layer is then converted to a raster dataset using the standard ArcGIS tool “Feature to Raster” and specifying “VEGTYPE” as the conversion “Field.”

Vegetation Categories are defined as follows: Category A areas may include trees or other tall vegetation but these are sparse and do not result in major breaks in line of sight between the sound source and observer; structures or other features are visible on the landscape beyond. Category B areas correspond to denser (approximately 50-80% cleared) vegetation between 1.3-2.0 m tall (e.g. thick maize). This vegetation is not much taller than a person, however the average person would have a difficulty seeing through it as visibility is restricted by dense stems. Category C and D areas both consist of dense forested areas (<50% cleared) that a person cannot see through. Type C areas consist of dense coniferous vegetation or “old growth” forests where attenuation is primarily due to
tree trunks causing breaks in the line of sight. Type D areas consist of full growth trees with a high density of branches, leaves, and undergrowth. These areas provide the greatest amount of attenuation.

10. Elevation Dataset: Select an elevation raster dataset (e.g. DEM, LiDAR) for your study area. At a minimum, the elevation dataset used in modeling must cover the area within a 4.0 kilometer (2.5 mile) radius from the sound source location.

11. Elevation Dataset Resolution (m): Choose the resolution of your elevation raster dataset. The resolution is based on the cell size of your dataset. To determine the cell size open ArcMap and add your elevation dataset to the map. Right click on the name of the elevation dataset in the Table of Contents, then select "Properties" at the bottom of the menu to open the Layer Properties window. Cell size is listed on the "Source" tab. If your dataset's cell size is not included in the standard options, select the next size larger.

12. Model Name (up to 9 characters): Choose a short name or nickname unique to this model run. Names must not exceed nine characters in length and cannot include a space. The underscore character is allowed. Note that if this model name has been used before, data from previous modeling runs completed with the same name will be overwritten or the tool may fail to function.

**Toolbox Outputs and Symbology Options**

After selecting the appropriate tool and entering the model inputs, the user clicks "OK" to run the analysis. While the tool runs, geoprocessing results will display in a
window indicating the model start and end times, and updating as the model proceeds through each step (see Figures G.3 and G.4).

Final model outputs include four rasters which follow the naming convention “pr_9CharName”, “ra_9CharName”, “ss_9CharName”, and “vs_9CharName” where “9CharName” is the Model Name specified by the user:

1. RA: This layer describes the SPL of the source as heard over the background SPL otherwise known as the “rise over ambient” dBA level. This is typically the layer of most interest.

2. PR: This layer depicts the general sound “propagation” pattern. Hypothetically, if the ambient SPL was 0 dB this is the extent to which sound would spread in relation to the elevation dataset.

3. SS: This layer also depicts a hypothetical scenario, “spherical spreading.” This layer would represent distance attenuation if there were no barriers present to block the spread of sound. The results are independent of the elevation dataset.

4. VS: This layer depicts a “viewshed” for the sound source in relation to the elevation dataset and height of the sound source.

Once modeling is complete and ArcMap is closed, it is possible to rename the geodatabase containing the modeling results (e.g. UniqueName.gdb) and create a new geodatabase within the Data folder named “Model_Output.gdb” prior to the next modeling run. Note that by doing this, you may need to update the ArcMap data sources for any
Figure G.3. Sample Soundshed Analysis – Variable Cover Tool Modeling Results

Executing: SoundshedVegMeters
C:\Users\Kristy\Documents\ArcGIS\Data\Copan\Locations\Acropolis.gdb\ld_6 6 330 96 1 79 90 "Veg Ambient\ambconst" "Ambients\Landcover Type" "R13 Basemaps\obs_urb_r13" 1.0 ID6tN

Start Time: Mon Dec 13 13:13:19 2021
Running script SoundshedVegMeters...
Warning: Data from prior runs of the Soundshed model will be deleted and results for the 330 Hz frequency band will be overwritten ...
Defining the study area ...
Calculating distance attenuation ...
Calculating atmospheric absorption loss for an elevation of 1998.5504883 ft, air temperature of 79 degrees, and 90% humidity ...
Calculating land cover impedance ...
Identifying barrier effects ...
Calculating decline in sound levels due to barrier loss ...
Calculating final noise propagation patterns and rise over ambient dBA ...
Completed script SoundshedVegMeters...
Succeeded at Mon Dec 13 13:19:36 2021 (Elapsed Time: 6 minutes 16 seconds)

layers displayed on the map to point to the renamed geodatabase (e.g. UniqueName.gdb) containing the previous run’s modeling results.

By default the rasters created by the model will be symbolized as stretched values along a black and white color ramp, where no-data values are represented by solid black, and the highest values are represented by white. These symbols must be changed to
correctly visualize results. At a minimum, right click each raster name in the ArcMap Table of Contents, select “Properties” and navigate to the Symbology tab. Check the box next to “Display Background Value:” and if necessary set the inputs to “0” and “as: no color”, though these inputs should be the default options. At the user’s discretion the “Color Ramp:” used to symbolize the data may also be changed. Select a color ramp in consideration of how the data will ultimately be displayed (i.e. printed in black and white VS color). Consideration should also be given to the clarity of the Color Ramp over the background or elevation dataset (it is often easier to view data if the color ramp represents a gradient between two colors or a saturation change gradient rather than a transition through many hues.
The raster data can alternately be displayed as “classified” data where colors are assigned to different numerical groupings or can be converted to vector data to be displayed using isolines (e.g. via the ArcGIS Spatial Analyst “Contour” tool). A combination of these methods can also be used to call attention to various aspects of the spread of sound, such as thresholds of passive and active audibility and/or speech intelligibility.

**Troubleshooting**

Occasionally the Archaeoacoustics toolbox may fail to run. When this happens the geoprocessing results window will display an error code. Because these codes are generated by ArcMap, not by the Archaeoacoustics toolbox, they are not always intuitive and can’t be searched online. The troubleshooting tips presented here target the most frequent errors.

1. **Cause:** spatial projection error

   **Issue:** The model appears to run correctly, but the data is “missing” – the layer is visible via the “zoom to layer” function, but it’s not located near the sound source.

   **Fix:** double check that all of the inputs datasets (raster and vector data) use the same spatial projection. Close and reopen ArcMap before modeling again.

2. **Cause:** Model output name exceeds the allowable length limits or has been used previously.
**Issue:** The model begins to run correctly, but fails with error code similar to that of Figure G.5.

**Figure G.5. Sample Soundsheed Analysis Tool Failure at Model Naming Step**

![Soundsheed Analysis Failure](image)

**Fix:** Review the Model_Output.gdb geodatabase for modeling results. Delete any feature classes which do not include the prefixes “pr_”, “ra_”, “ss_”, or “vs_” (e.g. layers named “salveg330” or “AmbientDba”) by right clicking the name of the feature class in ArcCatalog and selecting “Delete.” Close and reopen ArcMap before modeling again. Review the model output name to ensure it is unique (i.e. has not been used previously), does not exceed nine characters in length and does not include a space before modeling again.
3. **Cause:** Schema Lock

**Issue:** The model begins to run, but fails about midway through (most frequently it fails just after the geoprocessing results window displays “Calculating distance attenuation ...” (see Figure G.6).

**Figure G.6. Sample Soundshed Analysis Tool Failure due to Schema Lock**

![Soundshed Analysis Failure](image)

**Fix:** When running the model multiple times in a row, occasionally ArcMap will fail to remove a schema lock after geoprocessing is complete. This will prevent the tools from running and from overwriting data. Review the Model_Output.gdb geodatabase for modeling results. Delete any feature classes which do not include
the prefixes “pr_”, “ra_”, “ss_”, or “vs_” (e.g. layers named “salveg330” or “AmbientDb”) by right clicking the name of the feature class in ArcCatalog and selecting “Delete.” Close ArcMap, then delete and recreate the C:\SoundAnalysis\temp folder. Open ArcMap to resume modeling.

4. **Cause:** Elevation Dataset is too large

**Issue:** The model begins to run, but fails during the early steps (definition of study area, creation of ambient dataset) with a memory error.

**Fix:** This error most often occurs when using high resolution LiDAR data. Clip the extent of the elevation dataset used in modeling to the area within a 4.0 kilometer (2.5 mile) radius from the sound source location, and save the results as a new elevation dataset. If multiple sound source locations are being considered, first create a 4 km buffer around proximate sound source locations, then use the buffer to clip and then save the new elevation dataset. For widely distributed sound source locations multiple clipped elevation datasets may be required. Resume modeling using the new elevation dataset.
Appendix H: Permission to Include Previous Publications

Primeau and Witt 2018: Permission from Elsevier

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Soundscapes in the past: Investigating sound at the landscape level

Author: Kristy E. Primeau, David E. Witt
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This work is dedicated to my son, Xavier A. Dyson, who is my guiding force. Your innate urge to dance makes your mom smile and perhaps prompts some future research questions.