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RESEARCH

Paradigm or Practice? Situating GIS in Contemporary Archaeological Method and Theory

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Abstract
Geographic information systems (GIS) has been used in archaeology for four decades, and colloquially appears to have become a main tool in the geospatial aspects of archaeological practice. In this paper, we examine temporal trends in the use and/or mention of GIS in archaeological publications (books and journal articles), conference presentations, and websites. We gathered data through keyword searches and with formal sampling surveys and conducted both quantitative and qualitative analyses to characterize the changing nature and intensity of GIS use in archaeology over time, and then contextualize these trends with a narrative history of archaeological GIS. We show how archaeological GIS-use has grown from a few early adopters of the 1980s, through a slow initial integration phase in the 1990s, to a set of two major expansions in the 2000s and 2010s. While we find that applied use of GIS has grown to the point where it can be considered ubiquitous—if not completely universal—in the discipline, we also discovered that the major focus in archaeological GIS advancement is methodological rather than theoretical. We identify five roadblocks that we believe have hampered the development of a theory-rich archaeological GIS: (1) deficiencies in the archaeological GIS education model, (2) over-reliance on commercial software, (3) technical/technological barriers, (4) gaps in acceptance of GIS, and (5) the perception of GIS as "just a tool." We offer initial suggestions for ways forward to mitigate the effects of these roadblocks and build a more robust, theoretically sophisticated relationship with GIS in archaeology.

Keywords Geographic information systems · Archaeological theory · GIS methods and theory · Publication trends

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Introduction

Geographic information systems (GIS) and other geospatial technologies have been used in archaeological research for decades, and colloquially it seems clear that they are well integrated in the discipline. With the discovery of "lost" cities and urban landscapes by peering beneath tropical tree canopies with LiDAR, 3D scans of ancient monuments, reconstructions of submerged landscapes, "space archaeology," and other technologically advanced digital archaeological work grabbing the headlines (Brinkhof, 2021; Horton, 2016; Hurt, 2022; Maldonado, 2016; McGreevy, 2020; Rosa-Aquino, 2023), it would not be accurate to say that GIS and related geospatial technologies have not revolutionized archaeological *practice*. Indeed, McCoy (2021) documents a major increase in the prevalence of these technologies in archaeological research since 2005. And yet, the depth to which GIS or other geospatial tools have permeated archaeological *thought* is still unclear. For example, as recently as 2017, prominent GIS practitioners within the field have debated the impact of GIS on archaeological theory in a special issue of the *Journal of Archaeological Science* (Howey and Brouwer Burg, 2017a). In their introduction to that special issue, Howey and Brouwer Burg (2017b) describe a trajectory wherein GIS has grown from simply a set of spatial data management tools into a theory-building paradigm within archaeology. They assert that GIS is now considered a fundamental and central methodological *and* theoretical tool in archaeology. And yet, in the concluding article to the special issue, Lock and Pouncett (2017) still need to ask if GIS is "the answer" to *spatial thinking* in archaeology. More recently, a survey of 571 GIS publications indicates a lack of theoretical sophistication in archaeological applications of GIS (Menéndez-Marsh et al., 2023). This is illustrative of the current debate about the role of GIS in contemporary archaeology; there is little agreement about it even among dedicated GIS practitioners within the field.

Of the suite of geospatial tools commonly used by archaeologists (including GPS, high-resolution aerial and satellite imagery, LiDAR, and online mapping [McCoy, 2021]), GIS has the most pronounced history of theoretical engagement in the discipline, although mostly about the role of GIS technology in landscape archaeology (e.g., Gillings, 2012; Marcos Llobera, 2001; Wheatley, 1993, 2004). These debates were situated within the larger processualist–post-processualist debate, but differed from other such debates in that a major point of contention revolved around the digital and spatial nature of GIS technology and how that impacted archaeological representation and interpretation of space (Marcos Llobera, 2012). Further, GIS software suites are often multifaceted and incorporate or facilitate connection to other geospatial technologies and to different digital and computational techniques such as agent-based modeling (Davies et al., 2019; Ullah & Bergin, 2012), network science (Brughmans & Peeples, 2023; De Soto, 2019), statistical computing (Pourghasemi & Gokceoglu, 2019), reproducible science (Ducke, 2013), and 3D spatial studies (Landeschi, 2019). GIS therefore holds promise as a hub to unite these various strands of analysis into a more holistic digital and computational approach to spatiality in archaeology. Because of this, our focus in this paper is specifically centered on GIS, and understanding whether and how GIS is, or can become, a centralizing, theory-laden enterprise within archaeology.

We aim to situate the place of GIS in contemporary archaeology by mapping the historical trajectory of GIS-use in the discipline across publications in archaeological journals and books, presentations at archaeological conferences, and on websites related to archaeological applications of GIS. We undertake this survey with both quantitative and qualitative analytics, and explore these trends at broad and narrow levels, describing changes in the volume and nature of GIS-use in archaeology over time. Our study is both more directly focused on GIS than McCoy's (2021) work, and encompasses a broader and deeper set of scholarly works than does the recent survey by Menéndez-Marsh et al., (2023). Although not geographically exclusive, we approach this from a North American perspective, and view this study as an initial foray meant to spur a renewed focus on GIS theory in archaeology more widely. The reader is directed to Menéndez-Marsh et al., (2023) for insight into global trends in archaeological GIS. A major question that we hope to answer (or at least to make significant headway towards answering) is, "Has GIS fully saturated the practice of contemporary archaeology, and if so, in what ways, and when and how did this occur?" Inspired by Lock and Pouncett (2017), a second question we hope to address is, "Has GIS become a paradigm of spatial thinking within archaeology?" The answers to these questions will provide clarity about the current position of GIS within archaeology.

Methods

Recent research into publishing trends in archaeology has elucidated issues of prestige and power inequities (Beck et al., 2021), gender and diversity (Bardolph, 2014; Fulkerson & Tushingham, 2019), and the growth of methodological specialties (Brughmans & Peeples, 2017; Gaffney, 2008; McCoy, 2021; Menéndez-Marsh et al., 2023). In this paper, we focused on the ubiquity and character of GIS use within archaeology. We proceeded with a three-tiered approach to understanding GIS publication trends. The first phase was designed to provide a baseline, coarse-grained overview of the general temporal trends of GIS usage within the discipline across a broad set of publication types and venues. The second phase examines trends and types of archaeological GIS usage at a finer, more detailed scale in a targeted subset of publication venues. The final phase seeks to contextualize the results of the first two phases and to provide a more nuanced understanding of how archaeologists have used, are using, and will continue to use GIS within the discipline. Data analysis and plots for all analysis were conducted using the Pandas (McKinney, 2010), SciKit Learn (Pedregosa et al., 2011), Dython (Zychlinski, 2023), Natural Language ToolKit (NLTK) (Bird et al., 2009), Seaborn (Waskom, 2021), and Plotly (Plotly Technologies Inc., 2015) data analytic and plotting packages in the Python scripting language, and the code and datasets are made publicly available through the Open Science Framework with a persistent identifier and permalink (Ullah, 2023). The basics of our analysis methodology are provided in this section, and further details are provided in the supplementary text.

Phase 1: General Temporal Analyses

We began the first phase of research with a series of simple keyword searches for the term "GIS" within three corpuses: (1) the fifteen highest-ranked archaeology specific journals in Scopus, (2) our institutional library's main search page, limited to "books," and (3) a set of programs and abstracts from two major annual disciplinary conferences. Our methodology is briefly explained here, and details are included in the Supplemental Text, including a discussion of how and why our methodology differs from the PRISMA approach (Page et al., 2021) employed by Menéndez-Marsh et al., (2023).

We limited our Scopus search to the top fifteen non-interdisciplinary journals listed in the 2020 rankings in the subject, "Archeology, Social Sciences," which were the most recent rankings as of the time of analysis (Table 1). Search results were normalized by percentage of total number of articles published in each journal per year. Next, we collated a corpus of 242 book-form sources (monographs, edited volumes, and journal special issues) related to archaeological GIS, covering the period from 1990 through 2022. This list is not exhaustive, but all entries include title text, author names, dates, and publisher information, and 217 of the book entries also include publisher or librarian summaries. Finally, we compiled search results for "GIS" (Geographic Information Systems) from published conference schedules for the Society for American Archaeology (SAA) annual meeting and the European

Table 1 List of journals included in the Scopus keyword search phase, including the Scopus rank, journal abbreviations, and the total number of articles indexed in Scopus at the time of this research. Journal ranks are in the Scopus category of "Archeology, Social Sciences" for the 2020 ranking year

Scopus rank	Journal	Journal abbreviation	Total *n* (1982–2022)
1	Journal of Archaeological Research	JAR	282
2	Journal of Archaeological Method and Theory	JAMT	652
3	Journal of World Prehistory	JWP	323
4	Journal of Archaeological Science	JAS	9206
5	American Antiquity	AA	2545
6	Archaeological Prospection	AP	820
7	Digital Applications in Archaeology and Cultural Heritage	DAACH	198
8	Journal of Island and Coastal Archaeology	JICA	490
9	Journal of Social Archaeology	JSA	372
10	Journal of Anthropological Archaeology	JAA	1218
11	American Museum Novitates	AMN	521
12	World Archaeology	WA	1555
13	Archaeological and Anthropological Sciences	AAS	1622
14	Cambridge Archaeological Journal	CAJ	864
15	Environmental Archaeology	EA	609
			21,227

Association of Archaeologists (EAA) annual meeting for the period between 2004 and 2022 (with some gaps, see Supplemental Text).

Phase 2: Targeted Journal Assessment

We designed and implemented a set of three stratified random sampling frames to analyze the use of GIS within articles in three key, impactful, long-standing, and disciplinary journals selected to cover different areas within the archaeology-specific publishing sphere: (1) *American Antiquity* (representing a "flagship" journal of a major disciplinary society), (2) *Journal of Archaeological Sciences* (representing a main publisher of archaeological GIS research), and (3) *Journal of Archaeological Method and Theory* (representing a venue for longer-form theoretical and methodological discourse in the discipline). Notably, these three journals have held historically elevated statuses as important publishing venues within the discipline (Beck et al., 2021). The journals differ in mean article length, number of articles per issue, and topical and/or regional scope but produce comparable numbers of pages of text per issue (Table 2). We created three stratified sampling frames—one for each of the three journals—where the strata were publication years from 1995 to 2021. We used a random number generator to select one issue from each year for each journal. Within each selected issue, we focused only on original research articles and reports and excluded editorials, reviews, and commentary. This approach allowed us to generate representative samples for each journal across the full time range (17 years) while keeping survey labor requirements within reason and ensuring that each sample included a similar number of total pages and similar numbers of pages per year (Table 2). We recorded bibliographic information for each of the 855 articles included in the sample using the Zotero citation manager, and we manually reviewed each article to record several pieces of quantitative and qualitative data (Table 3 and 4). Quantitative metrics were normalized as values per page using the total page count within each stratum, which makes them reasonably comparable across the three journals.

We conducted keyword searches within each article using the search function of our PDF reader software for a set of "GIS search terms" (Table 3) and we separately also searched for the keyword "remote-sensing." We excluded search terms occurring in the bibliography of articles, but included terms in the title, abstract, and any other areas of text. We next visually examined each spatial figure in each article to categorize them based on how GIS was used or portrayed. The final figure categories (Table 3) indicate basic or methodological use of GIS ("GIS figures"), theoretical use of GIS ("GIS conceptual"), or the specific choice not to use GIS to make a spatial figure ("Maps/image NOT GIS"). All data was coded manually in a spreadsheet.

We then qualitatively categorized each article using the scheme laid out in Table 4. These categories delineate our expert opinions about the way GIS was employed in each sampled article taking into account all of the measurable variables (Table 3) that we examined for each article. We applied dimensionality reduction of the measured variables (Table 3) via non-metric multidimensional scaling (NMMDS) with the Bray–Curtis dissimilarity measure. NMMDS compresses the

Table 2 Summary data describing the samples drawn from the three journals targeted for in-depth analysis of the use of GIS in archaeological publications

	American Antiquity	Journal of Archaeological Method and Theory	Journal of Archaeological Science
Total number of articles surveyed	235	153	467
Total number of pages surveyed	4231	4563	4864
Mean number of pages per issue	157 (±32)	169 (±119)	180 (±130)
Mean number of articles per issue surveyed	9 (±2)	6 (±4)	18 (±13)
Mean number of pages per article	18 (±6)	30 (±14)	10 (±4)
Journal scope	Method and theory pertinent to New World archaeology	Method, theory, synthesis, and history of archaeology	Development and application of techniques and methodology in archaeology
Regional focus	North America or New World preferred	World/no restrictions	None stated/no restrictions

Table 3 Final quantitative variables measured for all articles analyzed in the targeted journal assessment

Variable	Measure
GIS search terms	Search hits for "GIS," "GISc," "geospatial," and "geoinformatic"
Remote-sensing	Search hits for "remote sensing"
GIS figures	Number of maps, air photos, satellite images, remotely sensed imagery, or 3D geospatial renderings created with GIS software
GIS conceptual	Number of diagrams or other conceptual figures related to the use or theorization of GIS
Maps/image NOT GIS	Number of maps, air photos, satellite images, remotely sensed imagery, or 3D geospatial renderings created without GIS

Table 4 Qualitative categories of GIS use in articles analyzed in the targeted journal assessment phase of the research

Categorization	Description
GIS not used	The article does not use GIS in any discernible way
Applications focused	GIS is used in the analysis or in creation of figures, but GIS methods or theory was not the main focus of the article
Methods focused	The article focused on developing GIS methods, or GIS as part of archaeological methods
Theory focused	The article focused on developing theory for GIS, or GIS as part of archaeological theory

variability across multiple recorded variables to two axes, allowing simple visual display of patterns or groupings in the original multidimensional dataset on a bivariate plot (also known as a "biplot," (Borg & Groenen, 2005)) on which the spatial distribution of points reflects gestalt trends in the original multidimensional dataset. We then tabulated a correlation ratio matrix across and between all of the measured variables (Table 3) and our nominal categorization (Table 4) to see how they correlate. The correlation ratio is a measure of association that accommodates both nominal and ordinal data types, and ranges from 0 to 1, with 0 indicating no relationship and 1 indicating a perfect relationship (Jacobson, 1972).

Phase 3: Natural Language Analysis

We used NLTK to conduct natural language analyses of text within three datasets: (1) the article titles of all 855 papers in the targeted journal assessment sample set, (2) titles from all 60 items in our book-form sample set, and (3) search results of 55 websites returned from a search for "archaeology GIS lab" (see Supplemental Text). NLTK provides a series of tools for extracting contextual meaning from a large set of prose, including word frequency ("ngram") analysis (Colton, 2015; Lobur et al., 2011). We applied a basic filter using NLTK tools to remove common "stopwords" (common prepositions and non-meaningful short words), non-meaningful numerical values, and punctuation from each corpus, and to pre-process the text into word lists per entry so that we could tabulate "ngram" counts, which are the number of unique occurrences of a word or word sequence in a corpus of text (Cavnar & Trenkle, 1994; Fürnkranz, 1998). These analyses allowed us to count the number of unique occurrences of individual words ("unigrams"), two-word sequences ("bigrams"), and, where applicable, three-word sequences ("trigrams"). We focused on the title words of articles and books, as these are often carefully worded as "mini-summaries" of the piece. Because website titles are often very short by design, however, we instead examined the longer summary descriptions that were also returned in the web search results (see Supplemental Text for details), which allowed us to extract a set ngrams more clearly related to the functions of these archaeological GIS laboratories. For the journal article titles, we were able to further separate our analyses by the GIS usage categories that we established during Phase 2 (Table 4).

Results

General Temporal Trends

The general temporal trend of the use of the term "GIS" in disciplinary archaeology journal articles is shown in Fig. 1. Our Scopus search found that 108 out of 21,227 indexed archaeology articles had the term "GIS" in the title between the period of 1982 and 2022. The average across this period was 2.63 (±3.22) articles per year, with an average of 55.46 (±158.13) articles per journal across all years. The earliest date for an archaeological article with GIS in the title was 1983. In the bottom panel of Fig. 1 it is shown that the first archaeological articles using "GIS" in the title appeared in the early 1980s, but article titles did not commonly include "GIS" until the 2000s. This limited search showed peak employment of the term "GIS" in article titles in the years 2019 ($n=11$), 2017 ($n=11$), and 2012 ($n=10$). Expanding the search fields to include abstracts and keywords pushes the trend of increasing usage of "GIS" back to the middle 1990s (Fig. 1, middle panel), and expanding the search area to all fields expands this further to the early 1990s (Fig. 1, top panel). When searching in all fields, we found 1474 articles employing the term "GIS," with an average of 35.95 (±47.05) articles per year, with an average of 98.27 (±157.13) articles per journal across all years. The earliest article in the search results hails from 1982—one year before the first article with "GIS" in the title. In the top panel of Fig. 1, there is an apparent increase in the slope of the temporal trend of these broader search returns starting in the early- and mid-2000s. This inflection is more apparent in the raw article counts (red line) than in the normalized values (blue lines), but by both measures, there has been a dramatic increase in general instances of the term "GIS" in the past 15 years. Our Scopus survey found five articles employing "GIS" in some way in 1999, which increased to 9, and then 11 articles in 2000 and 2001. Another inflection occurred between 2005 ($n=14$) to 2006 ($n=26$) and has continued to increase year-by-year with a few localized peaks and troughs to a high value in 2021 of $n=163$.

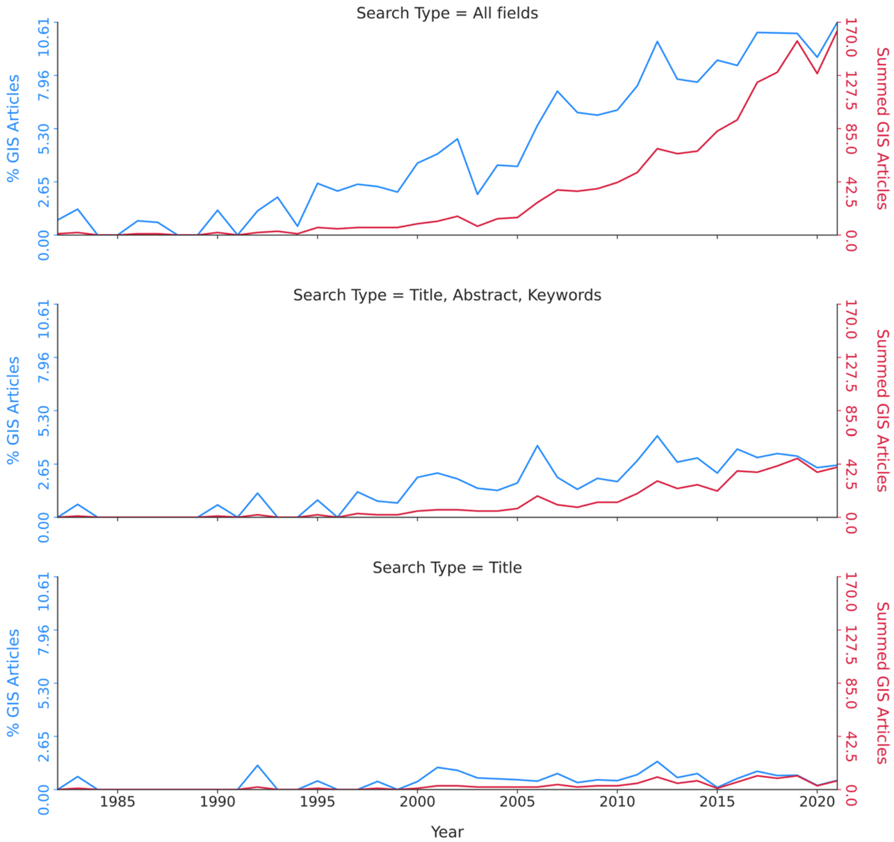

Fig. 1 Overall temporal results across all of the 15 top-ranked archaeology journals from the Scopus keyword search. Blue lines represent the number of positive search results for the "GIS" keyword normalized as percentages of total articles per year (left Y axis). Red lines represent the raw number of positive search results per year (right Y axis). The top panel shows results when the keyword search included all available search fields, the middle panel shows the results when the search was limited to the title, abstract, and keywords fields only, and the bottom panel shows the results when the search was limited to the title field only

When broken down by 4-year intervals and separated by journal (Fig. 2), the recent increase in the usage of "GIS" in articles (Scopus "All Fields" search) is driven by publication trends in a few key journals. Notably, the *Journal of Archaeological Science* is responsible for most articles employing the "GIS" keyword since the mid- to late-2000s (Fig. 2A). The peak number of "GIS" articles published in the *Journal of Archaeological Science* was 81 (out of 688) in 2018. *Archaeological and Anthropological Sciences* has more recently also begun to publish a considerable number of articles that employed the term "GIS," publishing 36 "GIS" articles out of 420 in 2019. However, when we normalized the raw counts of articles by the total number of articles published per year in each journal, a more nuanced trend appears that is inclusive of a substantial proportion of the top 15 archaeology

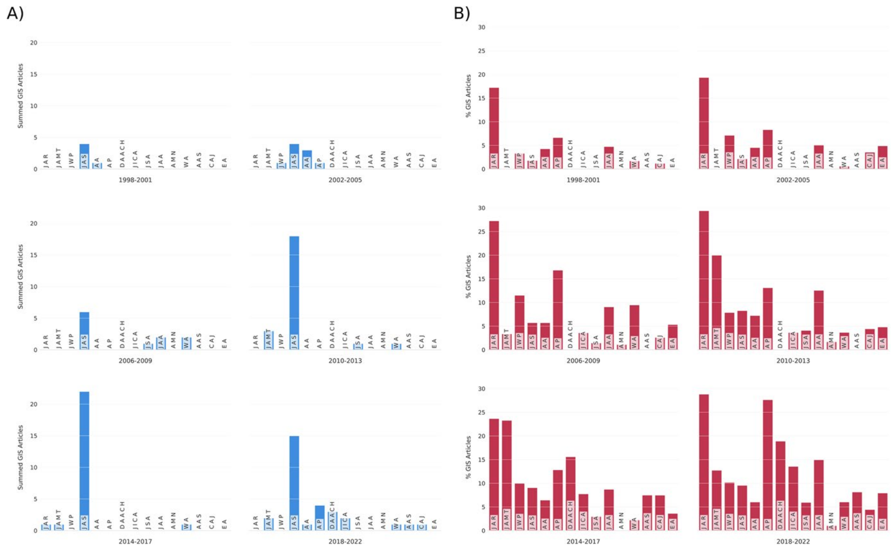

Fig. 2 Scopus keyword search results for "GIS" in the "All fields" search area in **A** total number of articles published in each journal and **B** percentages of total articles published in each journal within 4-year increments between 1998 and 2022 per each of the 15 top-ranked archaeology journals. See Table 1 for the list of journal abbreviations. For earlier dates, see Supplemental Fig. 1

journals (Fig. 2B). Journals such as *Archaeological Prospection* and the *Journal of Archaeological Method and Theory* are seen to have begun to publish a sizable proportion of articles per year that employ the term "GIS" relative to their total volume of publication in the mid- to late 1990s, which then dramatically increased in proportion in the mid- to late 2000s. The two largest percentages by year occurred in the *Journal of Archaeological Method and Theory*, which published 39.1% "GIS" articles (9 of 23) in 2012, and in *Archaeological Prospection*, which published 46.2% "GIS" articles (18 of 39) in 2021. In the past eight years *Digital Applications in Archaeology and Cultural Heritage*, a newer journal, has focused on publishing articles with a GIS focus, although this journal has a low publication volume overall. In the same period, *Archaeological and Anthropological Sciences* has emerged as a higher-volume journal that also publishes a large internal proportion of GIS-focused articles each year. In contrast, the *Journal of Archaeological Science*—notable for publishing the largest number of GIS articles by raw counts—actually puts out relatively little GIS-focused content relative to the total number of articles published in that journal each year. One other trend of note is that while *American Antiquity (*the flagship journal of the Society for American Archaeology) was an early adopter of articles employing GIS, it can neither by count nor by proportion be described as a major publication venue for GIS research in archaeology.

The number of monographs, textbooks, edited volumes, and special journal issues related to archaeological GIS published per year is shown in Fig. 3. The first sources found in our library search date to 1990, with at least two publications per year since that time. The trend is flat and low (modal value of 2) for the entire decade

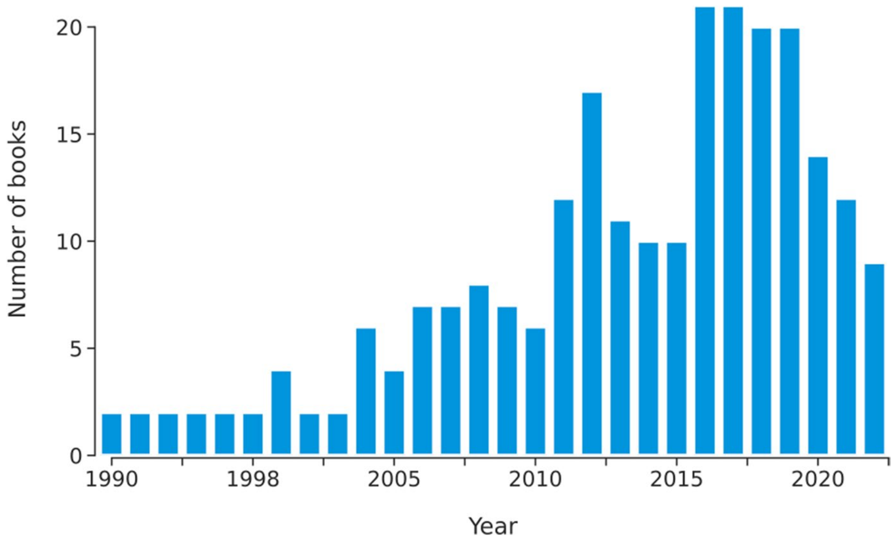

Fig. 3 The number of monographs, textbooks, edited volumes, and special journal issues related to archaeological GIS published per year over time

of the 1990s but begins to increase from 2004 onward. There is a sharp increase in the publication rate between 2010 ($n=6$) and 2011 ($n=12$), and another dramatic increase between 2015 ($n=10$) and 2016 ($n=21$). Peak publication rates occurred in 2016 and 2017 with $n=21$ publications, and there is a steep decline in annual publication rate between 2019 ($n=19$) and 2020 ($n=14$), with rates remaining low since then. Books often take longer to write and publish than individual journal articles, so it is too soon to tell if this lengthy but recent decline is simply a manifestation of the COVID-19 Pandemic or part of a longer-term decrease in book-form publication related to archaeological GIS. The overall average annual publication rate in this dataset is 8.57 ($\pm$6.34), with a median value of 7 book-form publications per year across the period from 1990 to 2022 (total $n=240$ for this period).

Our analysis of the temporal trends in the use of "GIS" and other GIS-related keywords in the published paper and poster abstracts of the SAA and EAA annual meetings is shown in Fig. 4. The temporal trends in both annual meetings indicate reasonable net growth in the use of GIS over time. However, the use of these keywords in SAA abstracts seems to have peaked between 2015 and 2017, and there has been a rapid decrease in usage of these terms since that time. Because this downward trend begins in 2017, it seems to have begun independently from the COVID-19 pandemic, although the trend has been exacerbated by pandemic effects from 2020 onwards. Interpolating across the years where only programs were available for the EAA annual meetings shows a steadier, if less rapid, expansion in the use of GIS-related keywords in these abstracts even until the present, with no indicated impact from the COVID-19 pandemic.

The average number of GIS-specific sessions or symposiums at the SAA annual meeting between 2004 and 2022 was 2.16 ($\pm$1.54), and the modal value was 3. The

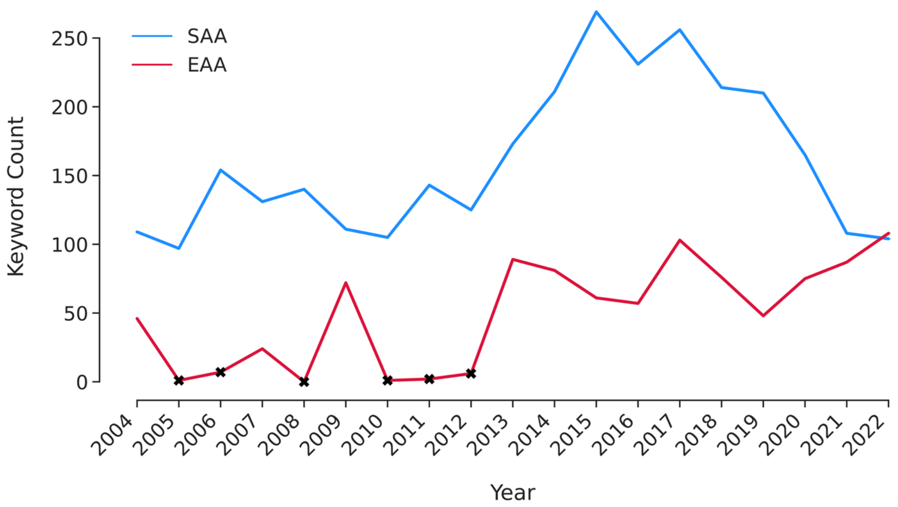

Fig. 4 Annual trends for amalgamated total counts of GIS-related keywords ("GIS," "GISc," "geospatial," "geoinformatic," and "geographic information system") from published abstracts or programs of the SAA and EAA annual meetings. Years where title-only programs were the only resource available are indicated by X's

average number of GIS sessions at the EAA annual meeting for this same period was 0.26 (±0.45), and the modal value was 0. These numbers are both low compared to the total number of sessions and symposiums that are typically scheduled at each meeting, but the SAA meetings more consistently offer at least one GIS-specific session, whereas the EAA meetings very rarely do so. Between 2004 and 2022, there were a total of 41 GIS-specific sessions at SAA meetings, and only five such sessions at EAA meetings.

Targeted Journal Assessment

We plotted the normalized frequency data of each search term and figure type (Table 3) in a series of radar plots in which each quantitative variable is represented by a spoke of the plot (Fig. 5). To explore the changing emphasis of the use of GIS within the three journals across time, the radar plots are broken into 4-year temporal bins and frequencies for each journal are separated by color. Although there is significant overlap between the three journals, they appear to separate when looking at the relationship of the number of maps or other images that likely were made *with* GIS software versus the number of similar types of figures that appeared to have been created *without* GIS software. The data from the *Journal of Archaeological Science* displays an overall trend of preferential use of GIS to create geospatial-related figures, whereas articles in *American Antiquity* more frequently use other techniques (e.g., graphics software or hand-drawing) in addition to GIS to create such figures. The *Journal of Archaeological Method and Theory* appears to publish few articles displaying maps of any kind, and no particular trend emerges in respect

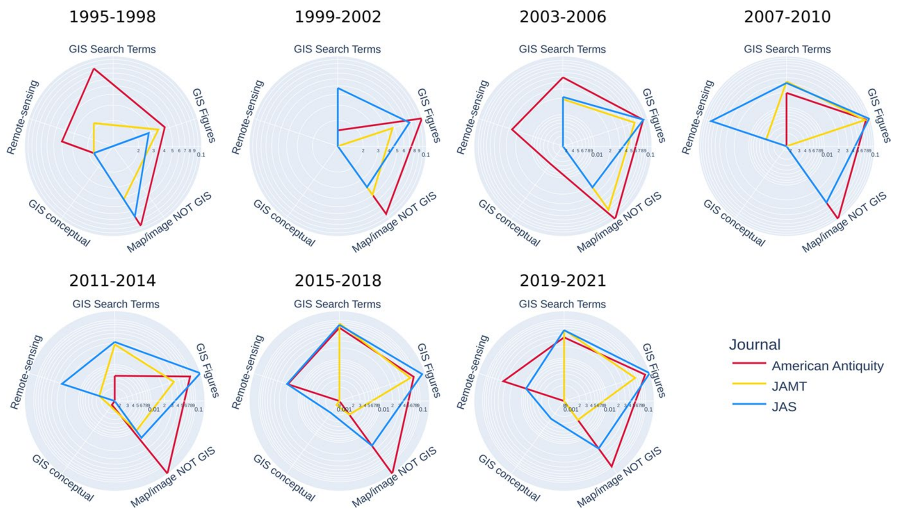

Fig. 5 Radar plots showing the normalized values for keyword search results and figure classifications for each of the three journals included in the Targeted Journal Assessment over time. Journals are separated by color, and each temporal interval is displaced as a distinct facet of the plot. Values are averaged within each temporal interval, and the polar axes of all plots are on logarithmic scales

to the preferential use of GIS to create those figures. Conceptual GIS figures are rare across time in all three journals, indicating that GIS use in the sampled articles has been practical or applied in nature. There is a small increase in the number of conceptual figures published in the *Journal of Archaeological Science* since 2015, which may indicate a slight shift in the focus on theory in GIS in that journal.

Table 5 lists the total count of GIS related articles in the sample analyzed by our team of GIS practitioners. On average, only 18.6% of articles in our total sample obviously used or discussed GIS in some way. Of the three included journals, this percentage was highest in the *Journal of Archaeological Method and Theory*, where nearly a quarter of all sampled articles employed or discussed GIS. Half of the 159 GIS-related articles in our sample were applications focused, and the remaining were evenly split between methods and theory foci. Looking within the three journals, the *Journal of Archaeological Science* is the most applications-focused, the *Journal of Archaeological Method and Theory* is the most methods-focused, and *American Antiquity* is the most theory focused, although these last two journals were similar overall.

The results of the NMMDS dimensionality reduction analysis are shown in Fig. 6. Articles that are similar across all of the measured variables (Table 3) appear close together in the two-dimensional space of the NMMDS biplot. We created a biplot for each of the three journals, and coded each point according to our final qualitative classification of the type of GIS usage employed in the article. Spatial clustering on the biplots loosely conforms to our qualitative categorizations across the three journals. The biplot for the *Journal of Archaeological Science* displays the clearest spatial clustering, which is also the most clearly aligned with our qualitative categories, whereas clustering is less apparent in the plot for *American Antiquity*, which also

Table 5 Counts and percentages of GIS-related articles in our targeted journal sample. The total number of articles employing GIS in any discernible way is reported for each of the three journals, and then broken down by within-journal percentages across the three categories of GIS-use based on the scheme outlined in Table 4

Journal	Total articles in sample	GIS-related articles (*n*, % of journal sample)	Applications focused (*n*, % of GIS articles)	Methods focused (*n*, % of GIS articles)	Theory focused (*n*, % of GIS articles)
American Antiquity	235	34 (14.5%)	15 (44.1%)	10 (29.4%)	9 (26.5%)
JAMT	153	38 (24.8%)	17 (44.7%)	12 (31.6%)	9 (23.7%)
JAS	467	87 (18.6%)	48 (55.2%)	18 (20.7%)	21 (24.1%)
All journals combined	855	159 (18.6%)	80 (50.3%)	40 (25.2%)	39 (24.5%)

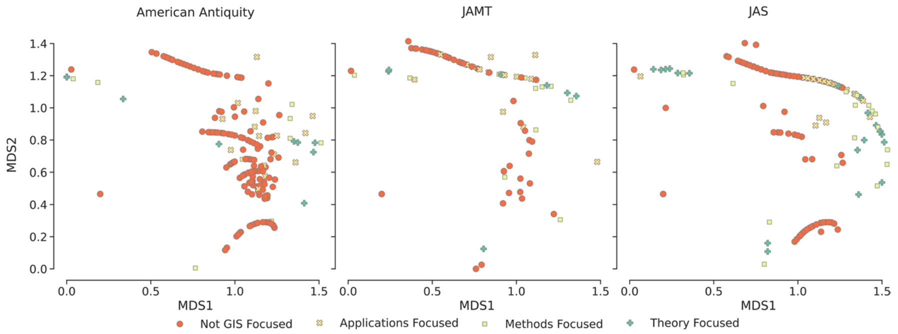

Fig. 6 Biplots showing the position of each sampled article from each of the three journals in the bivariate space created by NMMDS dimensionality reduction of the frequency data from the quantitative variables described in Table 3. Each point represents a single journal article. Colors and sizes of points are coded by our qualitative categorizations (see Table 4)

displays more spatial overlap between categories. The *Journal of Archaeological Method and Theory* displays spatial patterning intermediate to the other two journals, suggesting that NMMDS analysis can pick up at least the stylistic differences between the journals, and perhaps also differences related to journal scope and typical article foci. That said, NMMDS cannot fully segregate theory-focused GIS articles from methods-focused ones for any of the journals, suggesting that these types of articles employ similar numbers of the different figure types and GIS keywords.

Association analysis provides a different view of the relationship between the quantitative frequency data and our qualitative classification. Figure 7 shows correlation ratio matrices for each measured variable and our classification for each journal. These matrices are symmetrical, but show the level of correlation between different pairwise combinations. In particular, it is useful to examine the correlation ratio value between the qualitative classification and the individual quantitative variables, as that can inform about how the different types of figures and search terms are likely to be related to the ways GIS is employed in our article sample. Across all

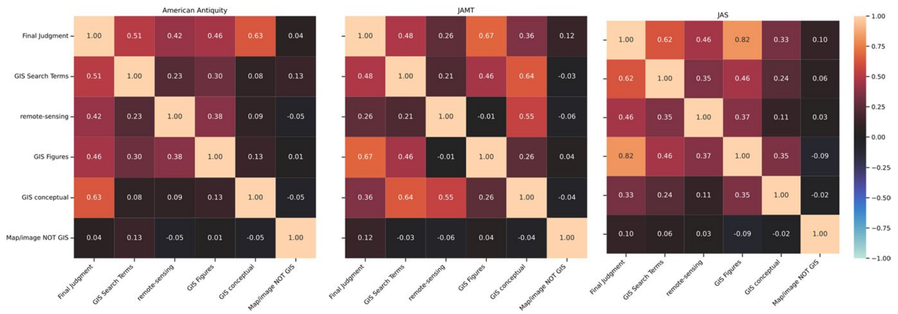

Fig. 7 Correlation ratio matrices showing the association between each pairwise combination of input quantitative variables (Table 3) and also with our final qualitative categorizations (Table 4). The matrices are symmetrical, and the levels of correlation are emphasized by the color scheme

three journals, the use of GIS keywords is strongly associated with the qualitative classification, and this association is particularly strong in the *Journal of Archaeological Science*. The use of GIS to create spatial figures is prominently correlated to qualitative classification in the *Journal of Archaeological Method and Theory*, and very positively correlated in the *Journal of Archaeological Science*. On the other hand, *American Antiquity* displays a much larger positive correlation between conceptual GIS figures and our qualitative classification than in the other two journals. Other notably large correlation ratio values occur between GIS conceptual figures and the "remote sensing" and other GIS keywords in the *Journal of Archaeological Method and Theory*. A final notable pattern is that the non-use of GIS when making spatial figures is uncorrelated to the use of the GIS and remote sensing keywords or to the presence of GIS-made figures and GIS conceptual figures across all three journals.

Finally, Fig. 8 tracks the cumulative percentage of articles in the types of GIS-use across time in each of our three sampled journals. Inflection points on these cumulative frequency plots indicate periods of rapid change in the rate of publication of articles of these three types. There is a brief initial rapid expansion of Application Focused articles in the *Journal of Archaeological Method and Theory* and *American Antiquity* around 2010. Another period of rapid increase in this article type occurred in the *Journal of Archaeological Method and Theory* between 2015 and now, and a similarly sharp increase occurred in *The Journal of Archaeological Science* between 2012 and 2015. These same periods in these two journals also saw rapid increases in the rate of publication of both methods focused and theory focused article types. While *American Antiquity* has continued to publish these types of articles, the rate of publication has not significantly changed over time.

Natural Language Analysis

Table 6 lists the frequencies of single word occurrences ("unigrams"), and Table 7 lists the frequencies of two-word sequences ("bigrams") for each category of GIS usage in the targeted journal article sample (a total set of 159 articles, Table 5). In general, the greater the frequency of a unigram or bigram, the more meaningful it is for contextualizing a corpus. However, common disciplinary terms with high ngram scores, such as "archaeolog/y/ical" or "analys/is/es," may not be as meaningful as some lower-frequency terms, such as "3d" or "landscape/s." Meaningful high frequency ngrams in the "GIS basic use" category include terms such as "new," "site/s," "case," "case study," "landscape," "patterns," and "provenience," suggesting basic reportage of primary data at the site or landscape scale. High frequency ngrams in the "GIS Methods" category include "approach," "model/l/ing," "data," "using," "remote sensing," "archaeological features," "archaeological site," "landscape/s," "mapping," and "study," among other terms that indicate manipulation of data on a regional or local geographic scale. Common meaningful ngrams in the "GIS theory" title words category include "gis" for the first time, as well as terms like "social," "system," "networks," "visibility," "3d," and "spatial," in addition to many of the terms that frequently occur in the "GIS methods" category. This

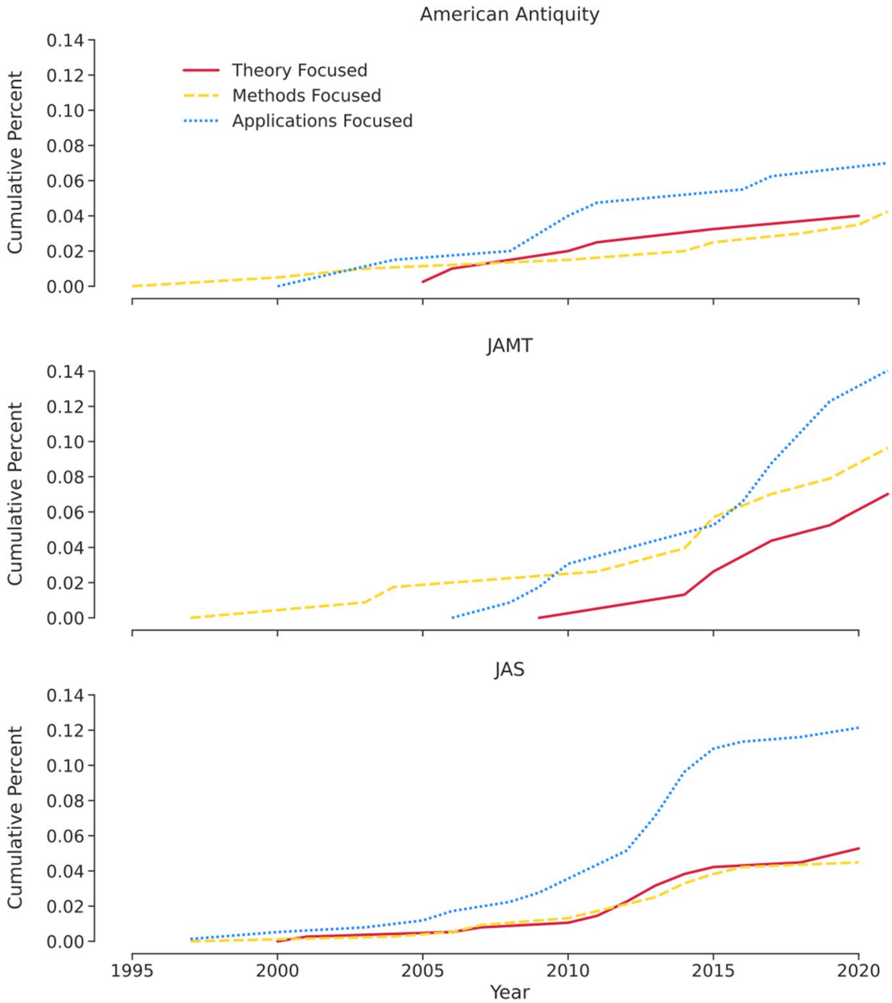

Fig. 8 Cumulative percentage plots of articles published in the three targeted journal assessment journals, separated by GIS usage categories over time

indicates a focus on extending capabilities within GIS or attempts at novel usages of GIS within archaeology.

Word frequency analysis of the title words in our database of 242 book-form publications resulted in 85 unigrams (Table 8) as well as 17 bigrams and 6 trigrams (Supplemental Table 3) with $n \geq 4$ frequency. The term "landscape/s" ($n = 30$) was the most frequent meaningful unigram, followed by "gis," "histor/y/ic/ical," "method/s/ology/ological," "approach/es," "analysis," "us/e/ing," "digital," perspective/s," "remote," "settlement/s," "spac/e/es/tial," "case," "3d," "applications," "mapping," "practice,", and "techniques". The term "remote sensing" was the most frequent bigram ($n = 12$), with "case study/ies," "cultural heritage" "rock

Table 6 Frequency and rank of unique single-word occurrences ("unigrams") in title text for all articles in the three categories of GIS usage at $n \geq 3$ frequency.. The input data includes article titles from all three journals combined by category. Unigram occurrences for "GIS basic use" category were truncated at $n \geq 3$ frequency, whereas "GIS methods" and "GIS theory" unigram occurrences were truncated at $n \geq 2$ frequency

GIS basic use			GIS methods			GIS theory		
Rank	Unigram	Count	Rank	Unigram	Count	Rank	Unigram	Count
1	Analysis/ses/tical	13	1	Archaeological	10	1	Archaeology/ical	10
2	Study/ies	13	2	Use/ing	7	2	Land/scape	7
3	Archaeology/ical	12	3	Analysis	6	3	Analysis	6
4	Site/s	12	4	Approach	5	4	GIS	5
5	Evidence	8	5	Data	5	5	Social	5
6	New	8	6	Landscape/s	5	6	Southern	5
7	West/ern	8	7	Model[l]ing	5	7	Using	5
8	Early	7	8	Imagery/ing	4	8	Ancient	4
9	Case	6	9	Stone	4	9	Case	4
10	Data	6	10	Age	3	10	Model/ing	4
11	Use/ing	6	11	Case	3	11	Settlement/s	4
12	Age	5	12	Ground	3	12	Sites	4
13	Bronze	5	13	Network	3	13	Spatial	4
14	Human	5	14	Remote	3	14	System	4
15	Landscape	5	15	Sensing	3	15	Age	3
16	Late	5	16	Site	3	16	Early	3
17	Prehistoric	5	17	Social	3	17	Iron	3
18	Settlement/s	5	18	Study	3	18	Networks	3
19	Ancient	4				19	Prehistoric	3
20	Example	4				20	Rock	3
21	Iron	4				21	Roman	3
22	Obsidian	4				22	Study	3
23	Patterns	4				23	Understanding	3
24	Provenance	4				24	Visibility	3
25	Southern	4						
26	Turkey	4						

art," "landscape archaeology," and "use/ing gis" as other notable high-frequency bigrams. Although several of the identified trigrams seemed to relate to the title of a particular CAA meeting proceedings volume, the term "remote sensing archaeology" ($n=4$) appears to be a valid independent trigram.

Finally, word frequency analysis of the descriptions of the 55 websites in our websearch sample set yielded 252 unigrams (Table 9) as well as 92 bigrams and 35 trigrams (Supplemental Table 4) with $n \geq 2$ frequency. Excluding any iteration or combination of the original search terms revealed "research/ers" ($n=31$) to be the most frequent meaningful unigram, followed by "data," "site/s," "analysis/yze/ing," "histor/y/ical," "map/s/ing," "landscape/s," "student/s" "cultural," "course/s,"

Table 7 Frequency and rank of unique two-word occurrences ("bigrams") in title text for all articles in the three categories of GIS usage. The input data includes article titles from all three journals combined by category. Bigram occurrences for all three categories were truncated at the n ≥ 2 frequency

Rank	GIS basic use		GIS methods		GIS theory	
	Bigram	Count	Bigram	Count	Bigram	Count
1	Case study	4	Remote sensing	3	Case study	3
2	Bronze age	3	Aerial photographs	2	Iron age	3
3	Early iron	2	Archaeological features	2	Ancient maya	2
4	Iron age	2	Archaeological site	2	Geographic information	2
5	Provenance study	2	Case study	2	Google earth	2
6	Toolstone procurement	2	Iberian Peninsula	2	Historical archaeological	2
7	US Southwest	2	Network analysis	2	Remote sensing	2
8					Rock art	2

"spatial," "field," "resource/s," "past," "geospatial," and "3d." The most frequent independently meaningful bigram was "remote sensing" ($n=5$), followed by "applied history," "spatial data," "cultural landscape," "cultural resources," "historic preservation," "open source," and "spatial analysis." The only meaningful trigrams that did not include the original search terms were "historic preservation office" and "human environment interaction" (both $n=2$).

Contextualization: a Narrative History of GIS in Archaeology

Our analytical results revealed temporal changes in the way GIS has been employed across various publication and presentation venues in our discipline. This section provides a brief narrative history and contextualization of the adoption and expansion of GIS use in archaeology over the past four decades. This history will help to situate the interpretation and recommendations that we make in the "Discussion" section and the "Roadblocks and Ways Forward" section below.

GIS was first brought to bear in archaeology in the 1980s during the era that Waters (2018) calls the "Commercial Period" in the history of GIS. Prior to this period, GIS was employed mainly in governmental or institutional arenas due to the expense and complexity of the computing infrastructure needed to make substantial use of it at the time (Waters, 2018). Early applications included the Canada Land Inventory (Hazlewood, 1970; and see Tomlinson, 1968) and in the compilation of geographic, waste, and water data for the city of New York (Anderson & Roark, 1969; de Neufville, 1969; Savas et al., 1969). A pivotal early event in the history of archaeological GIS occurred in 1985 during the 50th annual Society for American Archaeology meetings, when Kenneth Kvamme and Robert Hasentab organized a symposium titled, "*Computer-based Geographic Information Systems: A Tool of the*

Table 8 Unigram frequencies at the n ≥ 4 level for titles of 242 book-form publications related to archaeological GIS

Rank	Unigrams	Count	Rank	Unigrams	Count	Rank	Unigrams	Count
1	Archaeology/ical/ies/ists	121	30	Site/s	9	59	Urban	5
2	Landscape/s	30	31	Technology/ies	9	60	America/n	4
3	GIS	23	32	3d	8	61	Architecture	4
4	History/ic/ical	20	33	Applications	8	62	Change	4
5	Method/s/ology/ological	18	34	Geography/ic/ical	8	63	East	4
6	Approach/es	17	35	Theory/ies	8	64	Europe/ean	4
7	Analysis	15	36	War/fare	8	65	Geoarchaeology	4
8	Ancient	14	37	World	8	66	Global	4
9	Heritage	14	38	Conference	7	67	Human	4
10	Study/ies	14	39	North/ern	7	68	Interdisciplinary	4
11	New	13	40	Techniques	7	69	Interpretation	4
12	Sensing	13	41	Excavation/s	6	70	Introduction	4
13	Digital	12	42	Maritime	6	71	Making	4
14	Perspective/s	12	43	Prehistory/ic	6	72	Material	4
15	Remote	12	44	Rock	6	73	Medieval	4
16	Use/ing	12	45	Roman	6	74	Mediterranean	4
17	Age	11	46	South/ern	6	75	Modern	4
18	Culture/al	10	47	bc	5	76	People	4
19	Early	10	48	Bronze	5	77	Preservation	4
20	Model/s/l[l]ing	10	49	City	5	78	Report/s	4
21	Past	10	50	Computer	5	79	Research	4
22	Practice/s	10	51	Environment/al	5	80	Social	4
23	Settlement/s	10	52	Information	5	81	Society/ies	4
24	Space/es/tial	10	53	Ireland	5	82	Stone	4
25	Art	9	54	Middle	5	83	Survey/ing	4
26	Case	9	55	Quantitative	5	84	Systems	4
27	Eastern	9	56	Regional	5	85	Volume	4
28	Mapping	9	57	Science	5			
29	Proceedings	9	58	Time	5			

Future for Solving Problems in the Past" (Kvamme & Hasenstab, 1985). This session was the first venue that our team could identify where archaeologists publicly discussed the importance of GIS for aiding archaeological inquiry of the past, although Hasentab had earlier presented a paper on archaeological GIS at the 1983 SAA meeting (Hasenstab, 1983). Kvamme's earliest journal article explicitly using the term "Geographic Information Systems" in the title is Kvamme (1986), but his 1983 article in *Advances in Computer Archaeology* (Kvamme, 1983) appears to be his first use of what was GIS software for spatial analysis in archaeology. Other notable early publications from this period included Harris (1986) and Kellogg (1987). This latter

Table 9 Unigram frequencies at the n ≥ 4 level for website descriptions of 55 archaeological GIS laboratories

Rank	Unigram	Count	Rank	Unigram	Count	Rank	Unigram	Count
1	Archaeology/ical/ists	93	25	Anth/ropology	8	49	Photo/s/graphs	5
2	GIS	63	26	Past	8	50	Process/ing	5
3	Lab/s/oratory	51	27	Project/s	8	51	Program/s	5
4	Research/ers	31	28	State	8	52	Remote	5
5	Information	28	29	Department	7	53	Science/s	5
6	Data	27	30	Environment/al	7	54	Sensing	5
7	Site/s	26	31	Model/s/ling	7	55	Software	5
8	System/s	22	32	Based	6	56	Athena	4
9	Analysis/yze/yzing	19	33	Center	6	57	Central	4
10	Geographic	19	34	Collection/s	6	58	Designed	4
11	Use/d/ing	18	35	Database	6	59	Different	4
12	History/ic/ical	17	36	Digital	6	60	dr	4
13	Map/s/ing	16	37	Excavation/s	6	61	Instruction/al	4
14	Landscape/s	13	38	Geospatial	6	62	Office	4
15	Space/atial	13	39	Include/ing	6	63	Part/s	4
16	Student/s	13	40	Survey/s	6	64	Report	4
17	Appli/ed/cation/s	12	41	Technolog/y/ies	6	65	Study	4
18	Field/s	12	42	3d	5	66	Support/s	4
19	Course/s	11	43	Computer/tational	5	67	Teaches/ing	4
20	Cultural	11	44	Current/ly	5	68	Texsite	4
21	Record/s/ed	10	45	Human	5	69	Understanding	4
22	Univ/ersity	10	46	Learn	5	70	Vector	4
23	Provide/s	9	47	New	5	71	View/er	4
24	Resource/s	9	48	Open	5	72	Web	4

article is the oldest one that was included in our Scopus database, although it did cite two of the conference papers from 1985 SAA symposium: Lafferty (1985), and Kvamme (1985). Our temporal analyses (e.g., Figs. 1 and 3) reveal that this phase of early adoption was important, but that GIS was still not well integrated into archaeology at this time.

The next phase of the integration of GIS into archaeological practice mirrors the phase of GIS history that Waters (2018) deems the "Period of User Dominance and the Rise of GIScience" in the late 1980s and early 1990s. In archaeological publishing, this era could be considered to begin with the publication of Kvamme's, 1989 article in the *Journal of Archaeological Method and Theory*, "Geographic information systems in regional archaeological research and data management" (Kvamme, 1989). This was the first GIS-specific article to be published in a top-ranking archaeological journal, and it has been particularly impactful, having been cited at least 147 times according to Google Scholar as of the date of this writing. Kvamme followed this in 1990 with the first GIS papers published in *American Antiquity* (Kvamme, 1990a) and the *Journal of Archaeological Science* (Kvamme, 1990b). This era also saw the earliest book-form publications related to archaeological GIS. Of note are early books by Gillings and Wise (1990) and by Allen et al. (1990). Both books were early practical guides about how to use GIS for archaeological research. More broadly, support for GIS-based research and education grew during these years with the creation of the US National Science Foundation-funded "National Center for Geographic Information and Analysis" in 1988, which would later morph into the University Consortium for Geographic Information Science (UCGIS) in 1995 (Waters, 2018). Goodchild's (1992) galvanizing call to reinvent GIS as a scientific endeavor coincided with the rapid expansion of affordable, compact, and more approachable computers with graphical interfaces, and an ever-expanding array of GIS software solutions, such as ESRI's ArcInfo/ArcView, Clark Labs' IDRISI, and Golden Software's Surfer/MapViewer, to push GIS further into the mainstream of both academia and industry use. Although GIS would find ever-growing integration in archaeology throughout the 1990s, it is clear from our temporal analyses (Figs. 1 and 3) that the use of GIS would not become "mainstream" in the discipline until much later.

The late 1990s through the mid-2000s is the next era in the history of archaeological GIS integration. We consider this the first period of intensification of GIS-use in the discipline, where trends initiated in the previous period began to multiply. Computers and computer-use became more ubiquitous in society, and computing power and GIS software sophistication continued to increase rapidly (Waters, 2018). ESRI consolidated its GIS software into the popular ArcGIS suite (version 8) in 1999 and 2000 (updated to version 9 in 2004) (Maguire, 2000), and GRASS GIS (version 5) was released as open-source software in 1999 (GRASS Development Team, 2023a). In this era, GIS and "GIScience" development and training became housed more ubiquitously in Geography departments, and several GIS-specific journals were launched or expanded at this time (Waters, 2018). The UCGIS began to push for standardization in GIS training and used its popular annual meetings at venues for discussion of training standards (Sinton, 2017; Waters, 2013). In archaeology, several popular textbooks were published in this period, including Maschner (1996), Wescott and Brandon (1999), and Wheatley and Gillings (2002), as well as an important early edited volume (Lock & Stancic, 1995). These texts remain important instructional books for archaeologists interested in learning GIS.

The Shuttle Radar Topography Mission (SRTM) in 2000 marked a sea change in the availability of high-quality, global-coverage, accessible elevation data (Farr et al., 2007). Global SRTM digital elevation maps were first made available shortly after the mission, originally at 90-m horizontal resolution, and later at 60-m resolution. The availability of a high-quality, standardized global elevation dataset, along with high-resolution declassified imagery, such as CORONA (available since 1995), that could be freely or affordably downloaded from the USGS data clearinghouse was revolutionary for the expansion of GIS across the disciplines at this time (Farr et al., 2007), inclusive of archaeology (Hammer et al., 2022; e.g., Menze et al., 2006). Technological advances, such as fully functional (if cumbersome and heavy, as one of the authors vividly recalls) mobile GIS stations attached to high-precision

GPS receivers, also allowed for the tighter integration of GIS in archaeological fieldwork programs (Tripcevich, 2004).

By the early to mid-2000s, geospatial technology had matured to the point where some early adopters in archaeology could create seamless, fully digital GIS-based recordation systems. One academic example is "Cyber-Archaeology," pioneered by Tom Levy at the University of California, San Diego, which integrated digital recordation techniques with daily GIS database updates during fieldwork as early as the late 1990s and has since been extended with additional digital recording and analysis capabilities (Jones & Levy, 2018; Stanish & Levy, 2013). In an agency example, the South Coastal Information Center (SCIC)—one of the official archaeological data hubs in California—began the process of creating a fully digital record search system using GIS in 2001 by modifying a GIS database architecture inherited from the Jamestown Rediscovery project (Mallios, 2023). Initially, this database linked polygons of known archaeological sites in San Diego County with a basic catalog of site information overlaid on USGS base maps. Eventually, the SCIC worked with several local partners to create a fully searchable GIS database that interlinks site positions and geometries with digital site records and reports (Mallios, 2023).

The period encompassing the late 2000s through the middle 2010's represented the first exponential growth period for the use of GIS in the discipline. Another new version of ArcGIS was released in 2010 (version 10) that included mobile and cloud integrations (ESRI, 2004, 2010), and GRASS received a version update in 2006 (version 6) that included major refinements to the graphical interface to improve useability (Landa, 2007). The percentage of articles using the "GIS" keyword expanded across most of the top 15 archaeological journals (Fig. 2), and book-form publications related to archaeological GIS began to increase in frequency (Fig. 3) and included edited volumes dedicated to applications of GIS to archaeological problems, such as predictive modeling (Mehrer & Wescott, 2005), least cost analysis (White and Surface-Evans, 2012), and spatial analysis (Bevan & Lake, 2013), and to numerous book-length case-studies. Conolly and Lake published their excellent textbook in 2006 (Conolly & Lake, 2006) and Wheatley and Gillings' textbook was updated in 2013 (Wheatley & Gillings, 2013). SAA (and to a lesser extent EAA) presentations about or using GIS expanded towards the end of this time period (Fig. 4), and our analysis also indicates an expansion of the use of the "remote sensing" keyword in this period (Fig. 5), suggesting that archaeologists were now more regularly integrating remotely sensed data into GIS workflows. This period also exhibits small, but noticeable increases in applications focused GIS articles in the three targeted journals (Fig. 8); although this is more pronounced in the *Journal of Archaeological Science,* which also displays a marked increase in methods focused and theory focused articles towards the end of this time frame. Indeed, in the afterward to their influential 2006 edited volume about digital archaeology, Patrick Daly and Thomas L. Evans write that "[t]he use of computing is becoming an increasingly standard part of many endeavors [sic] within archaeology (Evans & Daly, 2006)."

All of these trends suggest that the technology and impetus to incorporate GIS in archaeological research and publication had matured by this time. This is the final period categorized by Waters (2018) and is one he describes as being categorized by cloud services, web-based mapping, and participatory GIS. Of particular importance for archaeology in this era was the initial release of Google Earth in 2005, and an update in 2009 when historical imagery layers were added to the platform (Luo et al., 2018). Google Earth brought easy access to very high-resolution imagery in a simple, GIS-like interface that could help archaeologists to "digitally" survey regions prior to fieldwork. Its low bar of entry also introduced digital geospatial data collection and a GIS-like workflow to many non-technical archaeologists (Luo et al., 2018). Although quite limited from an analytical standpoint, Google Earth nonetheless clearly stands as an important "bridge" to the furthered incorporation of GIS in standard archaeological workflows. A second important, although less immediately impactful event in this period was the founding of the Open Source Geospatial Foundation (OSGeo), which occurred in 2006, and brought together a wide variety of open-source GIS software and libraries, such as GRASS, QGIS, gvSIG, GDAL/OGR, PROJ, and others (Coetzee et al., 2020). What was once a bewildering maze of individual projects, codebases, and repositories spread out haphazardly across the internet became an organized, centralized, depot of open-source software, knowledge, and support that helped make these free alternatives accessible to more archaeologists.

This period also saw the introduction of standardized online digital repositories for storing and disseminating archaeological data, such as "the Digital Archaeological Record" (tDAR) in 2008 and Open Context in 2007, among others (E. C. Kansa, 2010; E. C. Kansa & Kansa, 2010; S. W. Kansa & Kansa, 2007; McManamon et al., 2017; Sheehan, 2015). Although these types of repositories were designed to host a range of data types, they support some common GIS data types, or at the very least, support basic text coordinate files. The expansion of open digital data in archaeology revolutionized our ability to reuse and compare data, including geospatial data (Huggett, 2015, 2017, 2020). At the same time, more sources of GIS data—now including many sources of high resolution and historical imagery—became available for free or minimal cost during this time, leading to a rapid increase in "remote sensing" publications in archaeological journals (Lasaponara & Masini, 2013).

The latest expansion of GIS-use in the discipline began in the late 2010s and is still underway. Here, the *Journal of Archaeological Method and Theory* exhibits a very marked increase in the rate of all three categories of GIS articles (Fig. 8), while the rates have mostly flattened out in the *Journal of Archaeological Science*. *American Antiquity*, on the other hand, has displayed a more gradual, but consistent increase in method and theory focused articles since the early 2000s. Nevertheless, the proportion of method focused and theory focused articles is the highest now than it has ever been, although applications focused articles are still the most common across all three journals (Fig. 8). If the pandemic period is discounted, a greater presence of GIS at professional meetings (Fig. 4) can be seen in this era as well. This indicates to us that archaeology is now in a "mature" phase of GIS practice. GIS is so well integrated into daily life that it would be hard *not* to use it in some way in archaeological practice—if only just for navigating a driving route to a field site! Mobile GIS is now in the palm of our hands, and our high-bandwidth smartphones can easily pull down ultra-high-resolution imagery while showing our position in real-time through connection to multiple constellations of positioning satellites. Some archaeologists appear to be capitalizing on these advancements (Banning & Hitchings, 2015; e.g., Dhonju et al., 2018; Fábrega-Álvarez & Lynch, 2022; Ullah, 2018; Ullah et al., 2019), and they are certainly now *using* the tool more ubiquitously and perhaps more intensively than ever before; it is especially apparent that archaeologists are now commonly using GIS to make map-type figures in our publications, and that archaeologists are very clearly using GIS-related terms when publishing (Figs. 6 and 7). Taken altogether this is positive, but it does not necessarily mean that archaeologists are innovating a place for GIS in archaeological theory. Indeed, our findings show that, despite recent increases, theory focused articles remain the rarest of the three categories of GIS use analyzed in our targeted journal study. Finally, it is also of note that there has not been a new textbook dedicated to archaeological GIS methods and theory published since 2006.

Discussion

Half of the GIS articles in our targeted journal survey were applications focused, and another quarter were methods focused (Table 5). Although there are some differences in the rates of increase in the different GIS-use types between the three publication venues that we explored in depth (Fig. 8), it is clear to us that the bulk of published GIS work in archaeology is relatively basic. The relative dearth (24.5%) of GIS articles solely focused on the development of theory for archaeological GIS is likely indicative of the adoptive nature of GIS in our discipline and the historical entrenchment of Geography as the "natural" home of GIS, and therefore also as the "natural" source of innovation in GIS method and/or theory (as described by Waters [2018]). This hesitance for theoretical innovation by archaeological GIS practitioners is reflected in the terms frequently used in the titles of GIS-related publications and websites: highly frequent ngrams such as "[case] study/ies," "site/s," "feature/s," "material culture," and "use/ing," which are all indicative of low-level GIS use (Table 6, 7, 8, and 9). When innovation in GIS is apparent, it is typically methodological, as indicated by ngrams such as, "method/s/ology/ological," "analysis/yze/yzing," "technique/s," "approach/es," "spatial analysis/es," and "remote sensing." Ngrams that indicate more sophisticated and/or theoretical use of GIS are rarer, even when theory focused articles were independently analyzed; "model/ing" is the 10th most common ngram, and "understanding" is the 23rd most common in this category of article. No version of the "theory/ies/etical" ngram ranks in any GIS-usage category within the targeted journal article title-words sample or in the descriptions of archaeological GIS laboratory websites, but appears at rank 35 for the book-form titles. Book titles do include a few other ngrams that indicate theoretical foci, such as "models/l[l]ing" and "interpretation," but methodological or applications ngrams such as "approach/es," "analysis," "study/ies," "practice/s," "mapping," "applications," and "techniques" are much more common. In this way, it appears that a common attitude towards GIS in archaeology is to view it as "yet another tool" borrowed from outside of the discipline.

Yet, GIS has become ever more central to the process of doing any type of spatial research, and with recent changes to funding calls from important agencies such as the US National Science Foundation that increasingly require a focus on "transformative science" (Waters, 2018), archaeologists have been at risk of being left behind compared to more GIS-forward disciplines. There have been several recent calls for reforming GIS as a human science, but these have been situated squarely within Geography (Goodchild, 2011; Merschdorf & Blaschke, 2018; e.g., Miller, 2007). Geography has embraced this critique—for example, the authors of a recent, important Human-GIS centered textbook, "GIS and the Social Sciences" (Ballas et al., 2017), are all geographers—but where is archaeology in all of this? We noted that the past 5–8 years has been a period of maturity in the ubiquity of GIS in archaeology. This is reflected in Heath-Stout and Jalbert's (2022) recent analysis of NSF funding in archaeology, which indicated that GIS was a top methodology mentioned in archaeological grant proposal abstracts and that GIS was the second most funded methodological area with 2005 funded proposals. To put that into perspective, the other top-funded areas were ceramic analysis and excavations, which have garnered only 2072 and 1956 funded proposals each. This is even more impressive considering that Heath-Stout and Jalbert's data set covered the entire period between 1955 and 2021—beginning well before the first usage of GIS in archaeology. Further, they found that the methodological realm of "digital" archaeology (including GIS) pulls in the second largest average total per grant (close to $201 k). However, funding in archaeological GIS is not distributed equitably, with close to 70% of PIs of funded research proposals being male (Heath-Stout & Jalbert, 2022). There is no indication that GIS is being proposed as more than a tool for managing spatial data and/or conducting spatial analyses in most of this research. Again, three quarters of GIS use in our article sample was either applications focused or methods focused. Further, in our review of the sets of ngrams from book and article titles and laboratory websites (Table 6, 7, 8, and 9), we found that major foci are methodological issues such as site discovery and predictive modeling, visibility or movement modeling, or landscape-scale spatial analysis. These are prominent issues, to be sure, but they are not new directions in archaeological GIS, let alone in integrative or transformative social science.

While the *Journal of Archaeological Method and Theory* and the *Journal of Archaeological Science* have shown high recent rates of growth in theory focused archaeological GIS articles (Fig. 8), *American Antiquity* maintains the largest overall proportion of theory focused GIS articles over all time (Table 5). We cannot say, therefore, that any one of these three prestigious journals is a preferred venue for discussion of GIS theory in archaeology. This is not to say, of course, that archaeologists have never published about the "theory" of GIS in archaeology; Mark Gillings, Piraye Hacıgüzeller, Trevor Harris, Di Hu, Marcos Llobera, Gary Lock, David Wheatley, Thomas Whitley, and Philip Verhagen, among others, have been writing extensively on the subject since the late 1990s, for example (Gillings, 1998; Hacıgüzeller, 2012; T. M. Harris & Lock, 1995; Hu, 2012; Marcos Llobera, 1996, 2003, 2011; Lock & Harris, 1997; Verhagen & Whitley, 2012; e.g., Wheatley, 1993, 2004; Wheatley & Gillings, 2000). There does not, however, seem to be an established centralized publication venue for these types of articles, and neither did we find any published book-length monographs or textbooks that we would characterize as mainly or solely focused on archaeological GIS theory.

Our investigations *did* find, however, that when concentrated discussions of theory for archaeological GIS do occur in print, they typically appear as edited volumes, special issues, or proceedings that follow from specially organized conference symposia dedicated to discussing theory in archaeological GIS. The first of these collections is a special issue of the *Journal of Archaeological Method and Theory*, titled, "In Search of the Middle Ground: Quantitative Spatial Techniques and Experiential Theory in Archaeology," and edited by Dorothy Graves McEwan and Kirsty Millican (2012), derived from a conference held the previous year at the University of Aberdeen that was specifically focused on "the possibilities and potentials of combining quantitative spatial studies with more human-centered [sic] and theoretically explicit approaches to past landscapes" (Graves McEwan & Millican, 2012). The seven papers in this special issue deal with the disjuncture between the supposed precision of digital geospatial technologies and the experience of ancient peoples on landscapes (Graves McEwan, 2012; Marcos Llobera, 2012; Rennell, 2012), technological advances in experiential GIS that are breaking and/or redefining previous theoretical silos (Eve, 2012; Millican, 2012; Pillatt, 2012), and, perhaps most relevant to the findings of this current paper, a call for archaeologists to build their own GIS-centric theories (Gillings, 2012).

The next collection appears in the proceedings of the 2015 Computer Applications in Archaeology meeting, collectively titled, "Keep the Revolution Going" (Campana et al., 2016). While CAA proceedings frequently contain chapters dedicated to archaeological GIS, there was a special focus this year with four of thirteen chapters dedicated to spatial analysis and GIS, including one chapter about "Theories, Questions and Methods" in spatial analysis (Campana et al., 2016). Although most papers in this collection are application or methodologically oriented, papers by Arnoldus-Huyzendveld et al. (2016) and Verhagen et al. (2016) stand out as important contributions to archaeological GIS theory. The papers make headway towards connecting GIS-based archaeological predictive modeling to resilience theory and land-use heritage theory, respectively. Also in this volume, Misiewicz et al. (2016) discuss how to teach GIS in archaeology, including how to teach GIS theory.

A second special journal issue, titled, "Archaeological GIS Today: Persistent Challenges, Pushing Old Boundaries, and Exploring New Horizons," and edited by Howey and Brouwer Burg (2017a), was published in *The Journal of Archaeological Science*, derived from an SAA symposium the previous year (Howey & Brouwer Burg, 2016), and contains twelve papers aimed at pushing GIS theory and practice forward within archaeology (Howey and Brouwer Burg, 2017b). Articles in this special issue address practical topics such as "big data" (McCoy, 2017), landscape affordances (Wernke et al., 2017), visibility modeling (Gillings, 2017), mobility modeling (Supernant, 2017), and 3D GIS (Richards-Rissetto, 2017), and tackle theoretical concerns, such as the place of GIS in archaeological storytelling (Earley-Spadoni, 2017), the idea of using GIS as experimental archaeology (Whitley, 2017), interrogating the inherent "quantitative" nature of GIS analyses (Brouwer Burg, 2017), and, as we recalled in the introduction to this paper, asked if GIS was "the answer" to spatial thinking in archaeology (Lock & Pouncett, 2017).

The most recent focused attention to GIS-adjacent theory in archaeology is contained in two volumes edited by Mark Gillings, Piraye Hacıgüzeller, and Gary Lock, titled "Re-Mapping Archaeology: Critical Perspectives, Alternative Mappings" (2019), and "Archaeological Spatial Analysis: a Methodological Guide" (2020a). Of the two, it is "Re-Mapping" that focuses on theorizing spatiality in archaeology, and resulted from a conference at the University of Leicester in 2015 and a follow-up symposium at the Theoretical Archaeology Group (TAG) conference later that year (Gillings, 2019). "Re-Mapping" is not about archaeological GIS per se, however, but rather a more general collation of archaeological thought about spatial representation and how spatiality is theorized in the discipline. Likewise, "Archaeological Spatial Analysis"—the methodologically-focused part of the pair of volumes—is not a compendium of GIS workflows *per se*, but rather a compilation of spatial techniques in archaeology which *could* be operationalized in a GIS.

We do not think it coincidental that these attempts at collating a body of theory related to GIS in archaeology were all published within the most recent era of GIS in archaeology. We posit that there is some positive feedback between the increase in these thoughtful discussions of archaeological GIS theory and the recent surge in GIS use and sophistication of application in the discipline. We find it particularly interesting, however, that all these collections originated as symposia or special conferences where *GIS theory* was a central concern. This implies that if archaeologists want to advance the place of GIS in archaeological theory, we will need to actively create spaces where archaeologists can come together to interactively discuss these issues.

Roadblocks and Ways Forward

At the dawn of the first era of GIS, Hazelwood encapsulated the human-centric nature of cartography and spatial reasoning when stating that "a map is not a record of reality but a generalized interpretation of what the compiler thinks are significant characteristics or relationships of an area for some purpose he [sic] considers worthwhile (1970, p. 75)." Archaeology has, from its inception, always been a spatial discipline (Gillings et al., 2020b), and maps and cartography have been central to the process of doing archaeological research since long before the digital age (Ullah, 2015). Archaeologists were among the first to see the benefits of commercialized GIS technology, and they have built a strong user-base for ever sophisticated applications of the technology in their problem domain. Yet, 40 years after those first forays into archaeological GIS applications, there still appears to be a relative lack of innovation in theory for archaeological GIS. How can it be that such an inherently spatial and human-centered discipline as archaeology has not taken a leading role in incorporating these computer-based spatial technologies within theories of human behavior? In this section we identify several "roadblocks" that we believe have stymied the deeper integration of GIS in archaeological thought and practice and offer some initial suggestions for how archaeologists can work through these challenges.

Roadblock 1: Nature of Education in Archaeological GIS

The first major roadblock that we suggest is a relative lack of a coherent educational pathway for archaeologists to learn about GIS theory and techniques that are specific to archaeological problems. There are currently very few cohesive programs available specifically for training at the undergraduate or graduate level in archaeological GIS. Our web search returned fifty-five current archaeological GIS labs or educational programs. While this is certainly an underapproximation of the total number of such entities, by comparison, Kholoshyn et al. (2021) estimated that there were over 2000 GIS programs at American and Canadian universities *by 1990*. As of 2015, Wikle (2015) estimated that there are over 200,000 Americans using GIS in some capacity in their professions, and that at least 7000 people had obtained a professional certification in GIS in the US alone. These "Geographic Information Systems Professionals" (GISPs) are certified by the GIS Certification Institute, which accredits GIS certificate programs that are overwhelmingly developed within Geography departments at 2- and 4-year institutions of higher education (Wikle, 2015). In a recent survey of GISPs, Mathews and Wikle (2017) found that the two most common majors for GISP holders were geography (40%) and "GIS" (25%, and a major typically offered by Geography departments). Engineering (9%), geology (8%), planning (6%), and computer science (5%) were the next largest majors, and all other majors combined—inclusive of Anthropology/Archaeology—comprised only 6% of GISPs. Most GISPs are not archaeologists, and so it is likely that many GIS professionals working in the archaeology industry (e.g., Cultural Resources Management) are not archaeologists by training. Conversely, most archaeologists who do learn to use GIS do so mainly or wholly through coursework and programs offered by Geography departments. In both situations, GIS practitioners are left to "figure out" how to use the tool in the domain of archaeology with little or no guidance about best practices—let alone theory—for archaeological GIS. While there may be opportunities for on-the-job training for new GIS professionals in archaeology and/or some Anthropology or Archaeology departments that offer a small number of courses specifically about archaeological GIS applications and/or theory, these are still relatively rare (at least in North America). There is no higher-level organization to help push for standardization in archaeological GIS training like that offered by the more general GISP certification. It is also unclear how useful GISP certification is in practice for archaeologists, other than serving as a basic qualification for applying to GIS specialist jobs in Cultural Resources Management (CRM) or agency employment. Overall, we believe that outsourcing GIS education has been one of the major roadblocks for innovation with GIS in the discipline.

To move forward, a more concerted effort should be made to provide some core curriculum competencies in GIS within archaeology/anthropology programs, much in the same way as other areas of archaeological specializations, such as lithic and ceramic analysis, zooarchaeology, or geoarchaeology. Although outside the scope of the current paper, a formal study of pedagogical practices in archaeological GIS training would be a good initial step in this direction. Even without that grounding, we offer here some simple options to improve current methods of GIS training in archaeology. At the undergraduate level, building blocks could include incorporation of modules or laboratory exercises that employ some basic GIS techniques and spatial thinking in core undergraduate archaeology classes, links to GIS-based resources such as 3D scans of world heritage sites for further exploration of archaeological topics in survey courses, and greater incorporation of GIS analyses in lectures and seminar readings. While we think that basic GIS skills can be satisfactorily learned in existing introductory GIS courses typically offered by Geography departments, Anthropology/Archaeology departments should offer at least one upper-division course focused on *archaeological* GIS methods *and* theory, where our students could begin to contextualize how GIS incorporates into archaeological research. This is the approach advocated by Misiewicz et al., (2016), and one of the authors (Ullah) has found this pedagogical approach to be effective in his mixed graduate-undergraduate archaeological GIS course taught at San Diego State University. A focus should be placed on the theoretical "why's" and "what if's" in archaeological GIS applications, in addition to the practical "what to do," "how to do it," and "when to do it's" that are typically taught. These questions are often intertwined in reality, and if the theoretical components are glossed over, the practical applications can suffer. If possible, internships, field schools, or special research projects that incorporate archaeological GIS as a major component could be offered as "capstone" experiences where students can put these lessons into practice.

At the graduate level, we believe that GIS should be employed as the main analytical tool in any course related to spatial analysis in archaeology, and that the idea of GIS as a theory-laden part of archaeological practice should be incorporated into core archaeological theory seminars. Ideally, graduate programs in archaeology would also offer at least one specific course about archaeological GIS suited to the graduate level (this could be a mixed graduate-undergraduate course). Theses/dissertation committees could encourage graduate students to think more critically about how they incorporate GIS and spatial thinking in their research and graduate programs could consider basic "GIS literacy" requirements or could accept advanced archaeological GIS training as a substitute for other requirements (such as foreign language proficiency). We recognize that some (or all) of these recommendations may be outside of the means of smaller departments, but if they are possible to implement, they could have a major impact on the nature of GIS use in the discipline by increasing the frequency of early exposure to GIS in archaeological problem contexts.

We also suggest a renewed focus on pedagogical techniques for teaching GIS in archaeology. One way to achieve this is by encouraging archaeological GIS educators to publish or otherwise share their curriculum. The simplest way to achieve this is by encouraging individual distribution of archaeological GIS teaching resources through such mechanisms as GitHub or Zenodo (e.g., Ullah, 2022), but a more impactful method would be to create a centralized, open repository dedicated for this purpose. One existing resource in this area is the "Post-Secondary Resources" collection of the Education and Outreach section of the SAA webpage (SAA, 2023). There currently are no resources related to archaeological GIS education included there, but some educational content about archaeological GIS has been recently published in the SAA journal *Advances in Archaeological Practice* (e.g., Davies et al., 2019; Fábrega-Álvarez & Lynch, 2022; Smith, 2020, 2020; Ullah, 2015; White, 2015). Critical discussion of GIS pedagogy should also be encouraged. GIS is most often mentioned in passing or as only a minor focus in publications about digital archaeological pedagogy (e.g., Carafa, 2013; Ulm et al., 2005; Visser et al., 2016). In contrast, however, Misiewicz et al. (2016) and Kvamme (2018) have made concerted efforts to specifically discuss GIS training in archaeology, which we believe is a more effective way to build a disciplinary consensus about GIS pedagogy. Organization of symposia at major conferences about archaeological GIS education could help further the dialog and build a shared knowledge base about effective pedagogical strategies that could be broadly applied in the discipline.

Another avenue to explore is a certification program in "archaeological GIS," like the GISP. This is logistically more difficult and would require an external oversight mechanism and consensus about the specific skills necessary for archaeological GIS professionals. Archaeology currently lacks any sort of disciplinary mechanism to accomplish this, although we note that the idea of certification in archaeological skills is not foreign to the discipline; the Register of Professional Archaeologists provides RPA and RA certifications, and there are myriad CRM certificate programs offered by 2 and 4-year institutions. It is clear, however, that advanced training in GIS can be a door-opener for employment in the industry (e.g., Matt, 2010), and although GISP certification may not actually train students in archaeological applications for GIS, it can help them break into archaeological GIS work.

Roadblock 2: (Over)reliance on Commercial Software

We acknowledge the long interconnection and often fruitful relationship of commercial GIS software companies and archaeology (e.g., Howland, 2019). There are benefits to enterprise GIS solutions, particularly in the CRM sphere where licensing and support costs can be wrapped into budgets and where timely turnaround for standard analyses is of major importance. Commercial solutions are often well-designed from a user-interface perspective, which makes them approachable and easy to learn. Basic operations are often "baked-in," allowing quick and easy access to repeated tasks. However, this situation can help exacerbate the mindset of GIS as a "black box" where you can do a set of basic spatial operations to repeatedly produce the same kinds of basic spatial products, such as site and overview maps and feature databases (Kvamme, 2018). Furthermore, the prohibitive cost of enterprise GIS software licenses can be restrictive for smaller entities or entities with limited budgets. This can lead to situations where only a small number of people have access to the GIS software, and/or where many of the more creative analytical tools in the software are left unaccessed because additional license fees are required to "unlock" them. We believe that this situation is another major roadblock to advancing a more nuanced and creative approach to archaeological GIS.

We encourage greater adoption of Free and Open Source Software (FOSS) GIS tools as means to circumvent this roadblock. FOSS does more than simply reduce overhead in budgets by eliminating licensing fees; it facilitates the scientific method by providing transparency in methodology right down to the source code and by placing very few limits on what can be done with the software (Ducke, 2012; Lake, 2012; Marwick et al., 2017; Orengo, 2015; Powell, 2012; Wilson & Edwards, 2015). By nature, commercial software is restrictive and opaque. Companies need to be secretive about their intellectual property—including source code—to remain competitive in the marketplace. They may also place heavy restrictions via the "End User License Agreement" (EULA) on when, where, and how their software or software output can be used, and often implement proprietary file formats to "lock" clients into their software ecosystems. Commercial software companies may also be less responsive to domain-specific enhancement requests from smaller user bases, such as the field of archaeology. FOSS software projects are the antithesis of this approach, and inherently support the ideals of open science and reproducibility (Ducke, 2012; Marwick et al., 2017). They use un- or minimally restrictive licenses, such as the GPL, BSD, or MIT licenses, which allow users to reuse, modify, or otherwise redistribute the software in any context (or, at minimum, in non-commercial contexts) (Lerner & Tirole, 2005). They encourage collaboration and contribution from the community, and so can more nimbly create tools for niche applications in specific domain contexts (Ducheneaut, 2005; Martínez-Torres & Díaz-Fernández, 2014). The code is available so that anyone can see the exact algorithms and calculations used in any operation, and algorithms are typically derived from peer-reviewed scientific literature. The downside of FOSS is that the projects can take time to grow to the point where they are accessible and well-supported by a large community of developers and users, and funding structures to support software development may be partial, for a fixed term, or tied to a larger research program (Steiniger & Hunter, 2013). Non-technical users are often intimidated by FOSS projects because they can initially be hard to install and run and may not be as user-friendly as commercial applications (Morgan & Finnegan, 2007). Depending on the maturity of the project, FOSS can also be limited in ability compared to an enterprise solution. This said, the FOSS GIS realm is, as of this writing, fully mature, and we believe that it is ready to supplant enterprise GIS in many archaeological applications (e.g., Benchekroun, 2022; Benchekroun & Ullah, 2021; Ducke, 2015; Orengo, 2015).

To be clear, we do not suggest or advocate that FOSS GIS completely replace enterprise GIS in all archaeological work. There is clearly still a place for commercial GIS in archaeology, particularly in the CRM sphere. However, FOSS GIS can and does work in many—if not most—other realms of archaeological practice. GVsig, for example, is developed by the Spanish government and is used for the majority of salvage archaeological work in Spain (Bibby & Ducke, 2017). More broadly, however, the OSGeo foundation has created the backbone for a seamless transition from commercial GIS to FOSS GIS in general. Specifically, the combination of QGIS and GRASS GIS provides many options for enhanced user experience and innovation in archaeological GIS applications. QGIS provides a user interface that will be familiar to users of commercial GIS software and provides simple access to many basic and necessary GIS operations, such as accessing imagery or map data from the cloud, creating professional, well-styled cartographic products, or maintaining spatial databases. QGIS integrates well into archaeological field work via the QField smartphone app, which enables a fully digital data acquisition, management, and analysis pipeline. A myriad of custom plugins and core analytical tools extend these capabilities into more advanced analyses. GRASS GIS provides access to even more advanced geospatial tools, including space–time analyses, 3D GIS, imagery analysis, scripting and customized addons (including several specifically designed for archaeological applications), and state-of-the-art modeling and analysis tools. Much of the power of GRASS can be accessed through QGIS via a plugin, and the two pieces of software make an excellent combination for both day-to-day GIS work, and advanced GIS applications. This is all achieved with no or minimal financial limitations or usage restrictions, which we believe will help to increase the sophistication of GIS use in the discipline.

Roadblock 3: Technical/Technological Barriers to Adoption/Innovation

There is a perception that GIS is highly "technical," and that one needs to specialize in GIS to be able to make use of it in research contexts. This probably stems from opinions formed in the early days of GIS adoption where this was very much true. User familiarity with computational devices has grown exponentially since then (Campbell-Kelly & Garcia-Swartz, 2015; Martin, 2021), and the complexity of most GIS software has been wrapped in better user interfaces with more access to help and tutorials than ever before. One issue the discipline is currently facing, however, is that despite the increasing ubiquity of *computational devices* in daily life, there has been a decline in *computer proficiency* due to prevalence of "app-based" operating systems on devices such as smartphones that are more frequently supplanting traditional computer systems in daily use (Anshari & Alas, 2015; Martin, 2021). Although there are GIS and GIS-like apps available for these types of systems (e.g. QField, Collector for ArcGIS, Mapit Spatial (Nowak et al., 2020)), advanced GIS work still largely requires a computer-based system. This divide is characterized by Lock and Pouncett (2017) as a difference between "informal" GIS systems versus "formal" GIS systems. Many current archaeological GIS learners may not have had broad exposure to, or experience with, directory-based computer operating systems (e.g., MS Windows, MacOS, Linux), and this may enhance "user fear" when faced with a "formal" computer-based GIS system (e.g., GRASS GIS, QGIS, ArcGIS).

Kvamme (2018) provides one avenue to progress in this area, which also relates to Roadblock 1, described above. He suggests that computer proficiency become part of the core curriculum in archaeological GIS training. Kvamme wants to see the simple, easy-to-use graphical user interfaces removed or scaled back on programs used in GIS training, which would be more possible with the FOSS tools suggested in response to our second Roadblock, above. A reasonable middle ground could be the use of "graphical" programming interfaces such as the Graphical Modeler tool in GRASS (GRASS Development Team, 2023b) where users create analysis workflows by chaining together "widgets" related to specific GIS operations. Here, GIS learners can specifically learn to visualize how the outputs of one operation feed into and are modified by the next without the need to learn specific scripting or programming languages. We would further suggest that basic computer literacy cannot be assumed for any part of archaeological pedagogy in post-secondary education. This may be exacerbated for programs offering a BA degree, which attract students who do not want math- or science-heavy programs of study and the emphasis on the use of highly technical computer software that often ensues. Early integration of basic computer skills into core curriculum such as archaeological methods or laboratory courses can help prepare students so that computer-based “formal” GIS systems will seem less intimidating.

It can also be hard to transform a vision of what one “wants” to do into a concrete geospatial analytical workflow due to unfamiliarity with all the technology and/or software that is needed to achieve it. At work here is the influence of both GIS-theory education gaps and computer proficiency training in archaeological curricula, and updates in these other areas are also likely to help make headway on this roadblock as well. Additionally, however, it seems clear that the proliferation of technology makes user-choice harder than ever when assembling a digital data collection and analysis pipeline. We advocate for the publication and open dissemination of workflows to help mitigate this difficulty. There are recent examples of this in 3D scanning and imaging (Beale & Beale, 2015; Benchekroun, 2022; Benchekroun & Ullah, 2021), mobile GIS and data collection (Ballsun-Stanton et al., 2018; Fábrega-Álvarez & Lynch, 2022; Nowak et al., 2020), and UAV (drone) survey (Olson & Rouse, 2018).

Roadblock 4: Gaps in Acceptance or Use of GIS

Archaeology is, in many ways, a conservative field. Although individual archaeologists are often early adopters of innovative technologies and methods, it often takes many years for these to penetrate into the core of disciplinary practice and thought. Our analysis of GIS use in this paper has shown that it has taken forty years for archaeological GIS *practice* to mature, but that the discipline has not yet achieved *theoretical* maturity. The temporal trends our analysis revealed indicates that there has been a generational shift in the general acceptance of GIS for basic tasks such as creation of overview and site maps. Some of this stems from the first three roadblocks above. If GIS software is perceived as too expensive, difficult to use, or too hard to learn, then the impetus to adopt it for these kinds of basic tasks is reduced, and archaeologists may be more comfortable using other tools, such as graphics programs or pre-prepared topographic base maps, they are already familiar with. Additionally, archaeologists in senior positions, such as PI’s, supervisors, theses advisors, and professors, may be reluctant to allow more sophisticated GIS approaches by employees, students, or interns because they feel unable to evaluate their work. It may be easier in these situations to push students or employees into less innovative, but more familiar workflows. It is also often hard to keep up with innovation in a rapidly advancing field such as GIS and geospatial technologies, and unfamiliarity with newer techniques can be an intimidating roadblock for some. As with any approach, it is possible to get “locked” into a particular way of doing things simply because it was the way that one learned to do it.

There is no clear single way through this roadblock. The best opportunity for advancement is a general plea for self-assessment, especially for those in senior positions. Progress towards the current ubiquitous applications- and methods-focused uses of GIS in the discipline occurred over a long time with variation in the rates of uptake in different periods. This is currently a time of sophisticated methodological application of GIS following the last period of rapid expansion in GIS use around 2015, and so it may simply be a matter of time before there is a follow-up expansion in theoretical sophistication. A greater willingness of those in supervisory positions to try new things—or at least to let employees or students try new things—could help spur this next period of rapid advancement sooner than later. Kelly (2020, p. 11), although writing for a slightly different reason, nonetheless sums up why this is important:

> Just think of all the new methods to keep up on: R programming, agent-based modeling, photogrammetry, Bayesian modeling, geometric morphometrics, general linear modeling, network analysis—you'll never have time to learn these. … And, of course, you're still needed. You've got the one thing new faculty don't have: decades of experience. … *You can put all those fancy new techniques into perspective and context.* [emphasis added]

Roadblock 5: Perception of GIS as "Merely a Tool"

The final roadblock that our team has identified is a general perception of GIS as "merely a tool" that can be used atheoretically in archaeological applications. A major symptom of this mindset in the discipline is the high proportion of applications focused and methods focused GIS-use that was revealed in our journal article survey. This mindset prevails for some of the same reasons explored in all the other roadblocks, not least the conceptualization of GIS as software rather than theory. Other disciplines have confronted this issue since as early as the middle 1990s (e.g., Aitken & Michel, 1995; Goodchild et al., 2007; Pickles, 1999; Sheppard, 1995; Warf & Sui, 2010) but it has been left untreated in archaeology until very recently (Brouwer Burg, 2017). This may partially stem from the dichotomy between academic and applied GIS work in the discipline in relation to the education pipelines for professional archaeological GIS practitioners. Sources of theory relevant to archaeological GIS work are not presented or made available in the typical training pipeline of GIS practitioners who are employed in the applied sector of our field (at least, not in North American archaeology). Further, there is currently little impetus for innovation or even methodologically or theoretically sophisticated GIS application in applied archaeology; the CRM industry, for example, typically only "needs" basic GIS applications such as the creation of site and overview maps and the creation and maintenance of basic geospatial databases. Because CRM is a business, emphasis is often on the bottom line; the basics *must* be covered, leaving any extended analysis or scholarly publication to be achieved only if there is budgetary excess or if employees can work on their own time (Lipe, 2009). Where more creative applications of GIS are applied in CRM, they are typically applied in either digital data collection/dissemination (e.g., Sarris et al., 2008; Tripcevich, 2004), or in predictive modeling (e.g., Johnstone, 2003; Mather and Watts, 1998; Mehrer, 2002).

From our collective set of experience in academic, CRM, and agency contexts, we think that progress on Roadblock 1 (education) will also work to ameliorate this roadblock as well. Specifically, we think increased access to formal training in archaeological applications (and theory) of GIS *within* archaeology/anthropology undergraduate and graduate programs will go a long way towards providing archaeological technicians with knowledge and experience in more sophisticated GIS applications (and spatial thinking), so that they can make the most of simple opportunities to do more with the basic geospatial datasets created by the CRM industry or other types of routine archaeological work. In practice, not much more effort is required to conduct, for example, cumulative viewshed analysis (Ullah, 2015), site catchment analysis (Ullah, 2011), or a set of least-cost analyses (White, 2015) to help contextualize the spatial patterning of contemporaneous sites in a project area once site locations have been digitized, a basic attribute table created, and a reasonably accurate DEM procured. These preconditions are frequently met by routine GIS work in CRM, and the value added from these additional GIS analyses could serve to increase the value of the CRM reports that must be created and filed in any case.

The three example analyses offered above are just the start of what could routinely be done by most archaeological GIS practitioners, and that is, again, why archaeological GIS educators need to offer our students a better theoretical grounding to match the potential methodological sophistication of the work they could do. This will also be enhanced by a more concerted effort to make GIS theory more coherent, accessible, and relevant to the kinds of geospatial tasks archaeologists commonly need to do. Our survey has shown that archaeologists *are* engaging with this theory, but not in any kind of organized or cohesive way. This has made it difficult for archaeology GIS learners to tap into a specific body of theory to help guide them towards more creative and sophisticated approaches to GIS in the discipline. Open sharing of GIS curricula (as suggested in our discussion of Roadblock 1, above) is one way to achieve this; particularly the sharing of GIS theory reading lists or "unauthorized companion" guides, such as the one made available by Fogelin (2019) for general archaeological theory. Although beyond the scope of this paper, a brief, non-exhaustive start to such a document could include affordance theory (Bernardini et al., 2013; Gillings, 2009, 2012; Kempf, 2020; Marcos Llobera, 2001; Wernke et al., 2017), visibility and experiential landscape theory (Bernardini et al., 2013; Dungan et al., 2018; Gillings, 2017; Graves McEwan, 2012; Marcos Llobera, 2001, 2003, 2012; Rennell, 2012; Wheatley & Gillings, 2000), least cost, wayfinding, and mobility theory (Franklin, 2020; Golledge, 1999; M. Llobera et al., 2011; Lock et al., 2014; Supernant, 2017; Ullah, 2011; White, 2015), deep-time landscape-scale GIS (Aldred & Lucas, 2019; C. T. Fisher & Feinman, 2005; Hill, 2006; Huisman et al., 2009; Lock & Harris, 1997), GIS as a model-based science (Church et al., 1999; Goodchild, 1992, 2011; Goodchild et al., 2007; Lock & Pouncett, 2017; Ullah & Bergin, 2012), people-centered/social GIS (Ballas et al., 2017; Miller, 2007; Pavlovskaya, 2016; Pickles, 1999; ten Bruggencate et al., 2016), and the ethics of GIS and digital archaeology (Chase et al., 2020; Crampton, 1995; Dennis, 2021; M. Fisher et al., 2021; Johnson et al., 2021; Myers, 2010; Nikolova, 2015).

Conclusion: Towards Archaeological GIS

Returning to the two questions that we laid out in the introduction to this article, we can confidently assert that GIS has fully saturated contemporary archaeological practice, but we, as did Menéndez-Marsh et al. (2023), would characterize the majority of GIS use in archaeology as mainly applications- or methods-based. Although the proportion of archaeologists who use GIS for basic tasks like creating maps or other spatial figures for publications has grown much over time, GIS is still not universally used for even these basic tasks, and archaeologists have yet to fully embrace GIS as a theory-laden activity, let alone a theory-building one, in our geospatial work. Archaeologists were early adopters of GIS, but through forces both internal and external to the discipline, they have not, overall, been as great a source of innovation in GIS methodology, theory, or education as they might have (or ought to have) been. Is this a symptom of a different kind of "quiet crisis" in [American] archaeology (sensu Killick & Goldberg, 2009)? The ubiquity of GIS applications in archaeology has also grown over time in a way that parallels the general evolution and larger adoption of GIS technologies (McCoy, 2021), and archaeologists have been attentive to opportunities for methodological improvements to our GIS work. We also asked, however, if GIS had become a *paradigm of spatial thinking* in archaeology. We have found that it is not yet; but we think that it could be! Archaeology stands now fully on the other side of the digital divide. If GIS is *not* "the answer" to spatial thinking in archaeology, as Lock and Pouncett (2017) asked, then it is hard to imagine what else would satisfactorily take its place. The analog roots of geospatial work in archaeology have been left far behind. Our data is ever more complex, large, and nuanced, and the methodological sophistication of our geospatial analytics needs to keep pace (Huggett, 2020; McCoy, 2017). Archaeology has done that as a discipline, but in a way that belies the richness of theory in our discipline's quest to understand the diverse ways in which humans and our socio-natural systems have lived and changed on this planet. If GIS *is* going to be the answer—and we think it should be (!)—then archaeology needs to transcend the derivative way in which its practitioners currently engage in/with GIS. Despite how sophisticated archaeological GIS work now is, it could be much more so if archaeologists could proactively and thoughtfully meld the tools GIS provides with archaeology's theories of human behavior and our discipline's long-term view of the story of humanity. If archaeologists are going to make progress on this issue, then they need to be clear-eyed about the current position of GIS in the discipline. Our survey provides this clarity; the remaining question is where, when, and how will archaeologists push forward? We believe that GIS stands to become more pivotal than ever in archaeology, but it will be up to all archaeologists to ensure that we take advantage of the full potential it can give to our work.

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Author Contribution All authors contributed to the study conception, design, and methodology. ZC, JM, and IU performed data collection. Data analysis and figure preparation was performed by IU, and IU, ZC, and JM interpreted the results. The first draft of the manuscript was written by IU, and all authors commented and contributed portions of text on all subsequent versions of the manuscript. All authors read and approved the final manuscript.

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Data Availability All data and analysis scripts employed in this research are made publicly available via an Open Science Framework repository (Ullah, 2023) at the following persistent identifier: DOI https://doi.org/10.17605/OSF.IO/3W7N8, and URL: https://osf.io/3w7n8/. All materials are released under the CC-By Attribution 4.0 International license, which allows reuse and dissemination of the material with the only restriction that the original source be cited/attributed in all derivations or redistributions of the material.

Declarations

Competing Interests The authors declare no competing interests.

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