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Research Paper

From viewsheds to viewscapes: Trends in landscape visibility and visual quality research

Nicole C. Inglis [a], Jelena Vukomanovic [a,b,*], Jennifer Costanza [c], Kunwar K. Singh [d]

[a] Center for Geospatial Analytics, North Carolina State University, Raleigh, NC, USA
[b] Department of Parks, Recreation and Tourism Management, North Carolina State University, Raleigh, NC, USA
[c] US Forest Service, Research Triangle Park, NC, USA
[d] AidData, College of William and Mary, Williamsburg, VA, USA

HIGHLIGHTS

- First multi-disciplinary systematic review of visibility & visual quality research.
- VVQ research increased 21-fold over past two decades.
- Advances in GIS allow more efficient, accurate visibility models.
- Bare-earth elevation models still dominate VVQ analysis despite limitations.
- Present 4-step framework for reporting + conceptual guidelines for future research.

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ABSTRACT

The study of visibility and visual quality (VVQ) spans scientific disciplines, methods, frameworks and eras. Recent advances in line-of-sight computation and geographic information systems (GIS) have propelled VVQ research into the realm of high performance computing via a cache of geospatial tools accessible to a broad range of research disciplines. However, in the disciplines that use VVQ analysis most (archaeology, architecture, geosciences and planning), methods and terminology can vary markedly, which may encumber interdisciplinary progress. A multidisciplinary systematic review of past VVQ research is timely to assess past efforts and effectively advance the field. In this study, we summarize the state of VVQ research in a systematic review of peer-reviewed publications spanning the past two decades. Our search yielded 528 total studies, 176 of which we reviewed in depth. VVQ analysis in peer-reviewed research increased 21-fold in the last 20 years, applied primarily in archaeology and natural resources research. We found that methods, tools and study designs varied across disciplines and scales. Research disproportionately represented the Global North and primarily employed medium resolution bare-earth elevation models, despite their known limitations. We propose a framework for standardized reporting of methods that emphasizes cross-disciplinary collaboration to propel visibility research into the future.

1. Introduction

Visibility and visual quality analysis is a critical aspect of human-environment interaction research. An observer's visual field is fundamental to the formation of spatial preferences (Nijhuis et al. 2011) and affects almost every aspect of human-environment experience on a vast range of scales, from internal emotions (Millar et al., 2021) to tourism economics (Schirpke, Timmermann, Tappeiner, & Tasser, 2016). Visibility and visual quality—which we will refer to as VVQ—analysis can be traced back more than half a century in multiple scientific domains, where it has become common practice in assessing and understanding visual experiences (Nijhuis et al. 2011). Given the growing accessibility and increasingly widespread use of VVQ analysis across a range of disciplines, there is an emerging need for cross-disciplinary understanding of current progress and future directions for the field.

VVQ analysis consists of calculating spatial models of what

* Corresponding author at: College of Natural Resources, Campus Box 8004, North Carolina State University, 2800 Faucette Dr., Raleigh, NC 27695, USA.
E-mail address: jvukoma@ncsu.edu (J. Vukomanovic).

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geographical areas can be seen from a set point, known as a viewshed (Fig. 1). The term "viewshed" was first published in 1967 by surveyor and landscape architect Clifford Tandy (Tandy, 1967). In 1968, computer scientists at the U.S. Forest Service developed a program called VIEWIT (Amidon & Elsner, 1968) that computed "seen area" based on gridded elevation cells. While VIEWIT's documentation doesn't use the terms "viewshed," "raster," or "GIS," it was a harbinger of VVQ research to come. The use of geospatial computation in modeling visibility has proliferated in recent decades, with advances in Geographic Information Systems (GIS) making visibility modeling accessible by operationalizing viewshed algorithms with easy-to-use and widely distributed software (ESRI, 2021; GRASSGIS, 2021). Historically, calculating line-of-sight for VVQ analysis has been a computationally intensive process (Zhao, Padmanabhan, & Wang, 2013). Researchers continue to develop new algorithms, leveraging high performance computing and GPU processing to reach new heights in computational efficiency and accuracy (Zhao et al., 2013; Zhu et al., 2019). Thus, GIS-based visibility models have become a mainstay of human-environment interaction research such as landscape planning (Anderson & Rex, 2019; Inglis & Vukomanovic, 2020), architecture (Rød & van der Meer, 2009; Weitkamp, 2011), archaeology (Garcia-Moreno, 2013; Van Dyke, Bocinsky, Windes, & Robinson, 2016) and natural resources (Chamberlain & Meitner, 2013; Depellegrin, 2016; Aben, Pellikka, & Travis, 2018).

VVQ analysis is applied with a wide variety of standards and practices, owing to its multidisciplinary applications. Various vocabulary terms represent overlapping concepts: for example, "isovist," "visualscape," "viewshed" and "line-of-sight", are scattered throughout the literature, which could lead to disparate interpretations (Table 1). For example, the term "viewshed" often refers to the area that can be seen from an observer point, but some studies interpret viewshed area as the quality of "openness" (Wilson, Lindsey, & Liu, 2008; Weitkamp, Bregt, & Van Lammeren, 2011). More recently, the term "viewscape" aims to characterize not just what can be seen, but how humans visually connect to their surrounding 3-dimensional terrain and built environment (Vukomanovic, Singh, Petrasova, & Vogler, 2018). While perhaps consistent in their respective fields, these discrepancies in terminology may encumber cross-disciplinary understanding and promote advancements in VVQ research that remain in disciplinary silos.

Interdisciplinary inquiry is integral to the geospatial sciences (Gilbert, 1909; Baerwald, 2010) and VVQ research exemplifies this

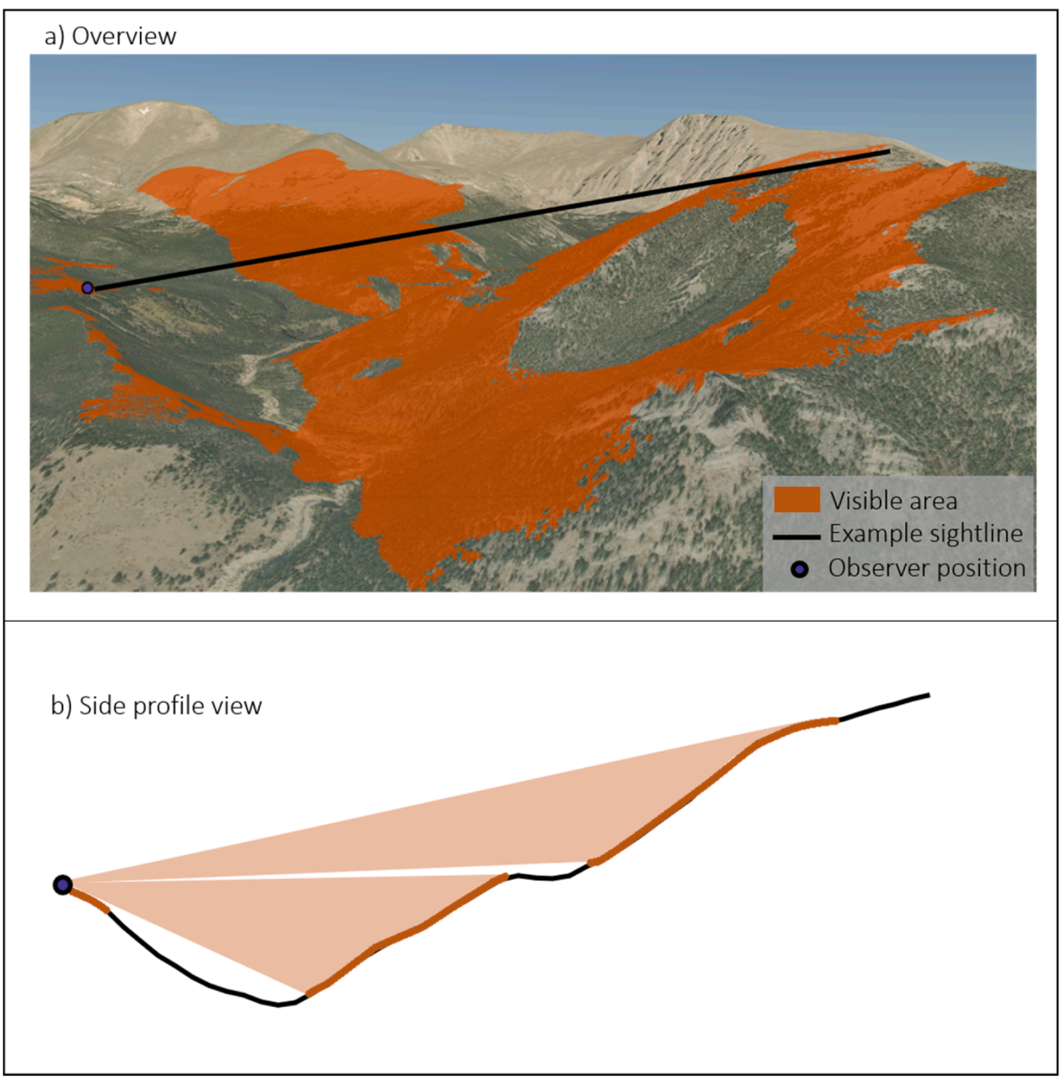

Fig. 1. An example of a viewshed computed in ArcGIS. Viewed in three dimensions (a), viewshed computation calculates whether a pixel can be seen from the observer location based on the elevation of the observer and of each pixel in the sightline. A side profile view (b) illustrates the visible areas within a single sightline. For illustrations and visual representations of how visibility and visual quality research are applied, please refer to examples of high resolution viewshed analysis (Tabik et al., 2013), visual quality and weighed analysis (Wheatley, 1995; Tenerelli, 2017), and 3D viewsheds (Fisher-Gewirtzman et al., 2013, Wróżyński et al., 2016).

Table 1
Examples of vocabulary definitions related to visibility and visual quality (VVQ) research across scientific disciplines.

Term	Definition	Discipline	Reference
Viewshed	*A geographical region visible from a location.* Tandy (1967) *coined the term as an analogy to a watershed.*	Multiple	Tandy, 1967; Nijhuis et al. 2011
Isovist	*The set of all points visible from a given vantage point in space and with respect to an environment.*	Architecture	Benedikt, 1979
Voxel	*Volumetric elements, representing a value on a regular 3D grid in space.*	Multiple	Fisher-Gewirtzman et al., 2013
Visualscape	*The spatial representation of any visual property generated by, or associated with, a spatial configuration.*	Multiple	Llobera, 2003
Viewscape	*The 3-dimensional visible portions of a landscape with which human observers form a connection.*	Natural resources	Vukomanovic et al., 2018
Viewnets	*Networks of locations where connections represent line-of-sight; a measure of intervisibility.*	Archaeology	Van Dyke et al., 2016

synergy between disciplines. Questions about visibility and visual quality often involve phenomena that cross disciplines, and that can benefit from cross-fertilization of ideas, technology, frameworks and insight (Baerwald, 2010). Given discrepancies in terminology (Table 1), and the rapid advancement of geospatial tools and technology—such as GPU-based parallel processing (Osterman, Benedičič, & Ritoša, 2014), lidar-derived surface models (Vukomanovic et al., 2018) and a glut of spatial big data (Lee & Kang, 2015) —the lack of recent and multidisciplinary reviews represents a mounting barrier in VVQ research. Now is the opportune moment for a literature review that takes stock of the state of the field, highlights research opportunities that leverage emerging geospatial technology, and serves as a launchpad for novel and interdisciplinary applications.

Past reviews of VVQ literature are either decades old or focused on a specific niche of VVQ analysis. A qualitative literature review in 2003 explored the use of GIS-based viewshed analysis in archaeology, where researchers use visibility models to locate historic sites and confirm theoretical suppositions (Lake, Woodman, & Mithen, 1998). Another qualitative review evaluated the influence of GIS-based visibility analysis across disciplines (Bishop, 2003). However, the technological advances in GIS and computing since this review suggest a timely opportunity to examine the growing field of VVQ research through a multidisciplinary lens. In 2018, researchers reviewed the usage of VVQ analysis in wildlife ecology research, encouraging future ecology researchers to consider viewsheds as a rich source of ecological information about the spatial patterns and behaviors of animals (Aben et al., 2018). A more recent literature review examined studies related to the visual assessment of landscapes, however it was limited to the journals Landscape and Urban Planning, Urban Ecology and Landscape Planning (Gobster, Ribe, & Palmer, 2019).The authors called for more systematic reviews with expanded definitions of what the visual quality research field entails beyond visual assessment. Our study directly builds on these past reviews and recommendations by conducting the first known multidisciplinary, systematic review of visibility and visual quality research.

In this study, we systematically reviewed and analyzed a subset of peer-reviewed research papers published from 2000 to 2019 to ask the following questions: 1) What are the geographic and temporal trends in VVQ research, and how do they vary across scientific discipline?, 2) What types of computational resources and algorithms are visibility researchers using?, and 3) How do different disciplines approach characterizing the visual quality and human dimensions of viewsheds? We describe the systematic review methods in section 2, and share descriptive statistics and visualizations of quantitative analysis results in section 3. In section 4, we elaborate on these results with a discussion of the papers reviewed and the implications of the trends and applications we observed. Finally, in section 5, we synthesize these concepts into a framework of suggested steps for VVQ researchers to consider in future studies.

The visual field is the primary way humans connect to our surroundings (Kandel et al., 2000), so visibility analysis could be a common lens through which to study human-landscape connection. Given advancements in geospatial technology and growing data availability, VVQ research has the potential to have far-reaching impacts in scientific research beyond architecture, archaeology and natural resources, and shape growing interdisciplinary research across human-environment systems. This study aims to promote insight into past VVQ research in order to empower researchers to bridge disciplinary divides and propel visibility analysis into the future.

2. Methods

We conducted a systematic literature review of peer-reviewed visibility and visual quality (VVQ) articles using the Web of Science database to characterize the past 20 years (2000–2019) of VVQ research. We collected a dictionary of search terms through preliminary analysis of the literature to capture the range of terms employed in visibility studies across disciplines. We aimed to limit our search to articles that digitally computed visibility using gridded elevation surfaces or other 3-dimensional terrain models. We used these terms to target topics using the search phrase "viewshed OR viewscape OR (line-of-sight AND GIS) OR (visibility AND GIS)." To characterize the recent evolution of VVQ research, we constrained our search to articles published between 2000 and 2019. We limited our search to articles published in English.

For all articles found through this search, we recorded the journal and year published. We then randomly selected one-third of the articles for detailed review (e.g. Fardila, Kelly, Moore, & McCarthy, 2017; Madureira & Monteiro, 2021). The articles selected for detailed review were analyzed to evaluate when, where, how and why VVQ research was conducted (Table 2).

For each paper we recorded the year of publication, journal, study location and scientific discipline, which we categorized into seven disciplinary domains based on preliminary analysis of the literature (Table 2). The spatial extent of studies were classified into four categories: local ($<$10 km^2), landscape (10 to 1,000 km^2), regional (1,000 to 1,000,000 km^2) and continental ($>$1,000,000 km^2) (Turner, 2001; Meentemeyer, Haas, & Václavík, 2012). Here, extent refers to the area of the entire study, but does not necessarily indicate complete coverage. For example, if a study computed viewsheds in several cities around the Northeastern U.S., it was considered a regional study. We recorded whether visual quality metrics were assessed (Table 1). If a study relied exclusively on viewshed area (size) as a metric, that measurement was not considered visual quality. We determined whether researchers weighted some visible aspects of the landscape as more important than others. This category included distance weighting or distance decay, where objects further away are considered less important (e.g. fuzzy viewsheds; Higuchi, 1984); vertical weighting, in which height or prominence was considered (Shang & Bishop, 2000); and object weighting, where objects of specified types or seen by more observers are considered more important (e.g. cumulative viewsheds; Wheatley, 1995).

We recorded the resolution, source and data structure (DEM, DSM or volumetric) of the elevation model (Table 2). Data sources were classified by collection mechanism: Light Detection and Ranging (lidar) systems, unmanned aerial system (UAS) and satellite. lidar data collected via UAS were categorized as "lidar." In studies that used United States Geological Survey (USGS) DEMs, which incorporate multiple data

Table 2
Review categories and descriptions.

Category	Classifications	Description/examples
Study extent	Local	*< 10 km^2; if not specified, studies comprising a single point or focused on a single location.*
	Landscape	*10 km^2 to 1,000 km^2*
	Regional	*1,000 to 1,00,000 km^2*
	Continental	*Spans continent such as contiguous United States or Europe*
	Undefined	
Visual quality	Greenness	*NDVI or other vegetation index*
Measures of quality of the area within viewsheds	Terrain ruggedness	*Degree of variety and prominence of terrain features*
	Land cover	*Proportion of land cover types*
	Built environment	*Measures of building presence, building height, urban visual quality*
	None	
Weighting	Distance	*Objects closer or farther from observer considered more important*
How are different features within a viewshed quantitatively weighted?	Vertical	*Terrain or objects at higher elevations above ground are considered more important*
	Object	*Objects of certain types or seen by more observers are considered more important*
	None	
Domain	Computational	*Viewshed algorithm development, parallel computing methods*
Scientific discipline	Archaeology	*Reconstructing ancient sites or travel routes, modeling archaeological sites*
	Energy	*Energy development e.g. wind turbines, oil and gas*
	Natural resources	*Wildlife ecology, ecosystem services, forestry, watershed*
	Urban planning	*City parks, development planning, transportation*
	Real estate	*Hedonic price modeling, development modeling*
	Surveillance	*Camera placement, military applications*
Elevation data model	DEM	*Bare-earth elevation model*
	DSM	*Elevation model with natural and built terrain features*
Elevation data source	Satellite	*Elevation derived from satellite interferometry (such as SRTM) or imagery*
How was the elevation model derived?	Lidar	*Ground and airborne light-detecting and ranging technology*
	UAS	*Unmanned aerial systems*
	Direct measure	*Measurements taken in field, or estimated from previously-collected data*
	Undefined	
Resolution of elevation model	High ≤ 10 m	
	Medium > 10 m and ≤ 30 m	
	Low > 30 m	
	Multi-resolution	
	Undefined	
Human dimensions	Participatory mapping or modeling	
How were human preferences and values incorporated into the analysis?	Stated or revealed preference	*Surveys*
	Social media	*Data scraping from social media data*
	None	

sources, we referred to USGS specifications on which sources are used for which data resolution (Archuleta et al., 2017). We also reported the number of vantage points from which viewsheds were calculated, as well as what software or programming language was used (Table 2).

Three of the authors manually reviewed each paper to record the relevant attributes. Manual coding of each study's attributes enabled the depth of interpretation needed for a detailed review. The use of predetermined categories and attributes allowed for a standardized process. To ensure consistency across reviewers, all three reviewed the same five papers and compared results. This quality control measure helped ensure that reviewers interpreted classification categories consistently. During the detailed review, we excluded papers that didn't conduct visibility analysis, despite containing the search terms, as well as non-English language articles where only the abstract was written in English.

3. Results

3.1. Geographic and disciplinary research trends

The Web of Science search yielded 528 peer-reviewed articles published between 2000 and 2019. The number of publications increased steadily over the study period (Fig. 2; black line), starting with 3 publications in 2000 and 63 in 2019 (21x more). The International Journal of Geographical Information Science published the most VVQ research (4.5% of search results), followed by Landscape and Urban Planning (3.8%) and the Journal of Archaeological Science (3.6%). Of the 267 journals represented in the database, 195 (73%) published a single VVQ paper.

We reviewed 176 articles in depth and excluded 54 (30.6%) from the remainder of the analysis because they did not conduct a quantitative or GIS-based visibility analysis. Of the 122 remaining articles, more than half were in the disciplinary domains of archaeology (33, 27%) or natural resources (29, 23.8%) (Fig. 2). The next most common research domain was urban planning (20, 16.4%), followed by computational studies (14, 11.5%), energy (12, 9.8%), surveillance (10, 8.2%) and real estate (4, 3.3%). Computational studies were those that advanced the efficiency, accuracy or speed of viewshed calculations, but were either not applied to real terrain/locations or lacked direct application.

The largest number of studies (43, 35.2%) were conducted at the landscape extent (10–1000 km^2), followed by local (40 or 32.8% at < 10 km^2) and regional extents (30 or 24.6% at 1,000–1,000,000 km^2) (Table 2; Fig. 2). Two natural resource studies and one urban planning study covered continental extents, while six computational studies did not define spatial extent. Urban planning studies primarily had small (local) extents (16 or 80% of urban planning studies), while archaeology studies were most likely to have landscape extents (16 or 48.5% of archeology studies). Regional and continental extents were less common (24.6% and 2.5% of total studies, respectively) and were most frequently used in natural resource research (33.3% of regional studies and 66.7% of continental studies).

Europe had the largest share of research (41.6%) of any continent, while the United States was the country with the most research at 30 total papers (24.6%; Fig. 3). Eleven (9%) papers were published in Spain, the most in Europe. The Global South represented 18% (22) of

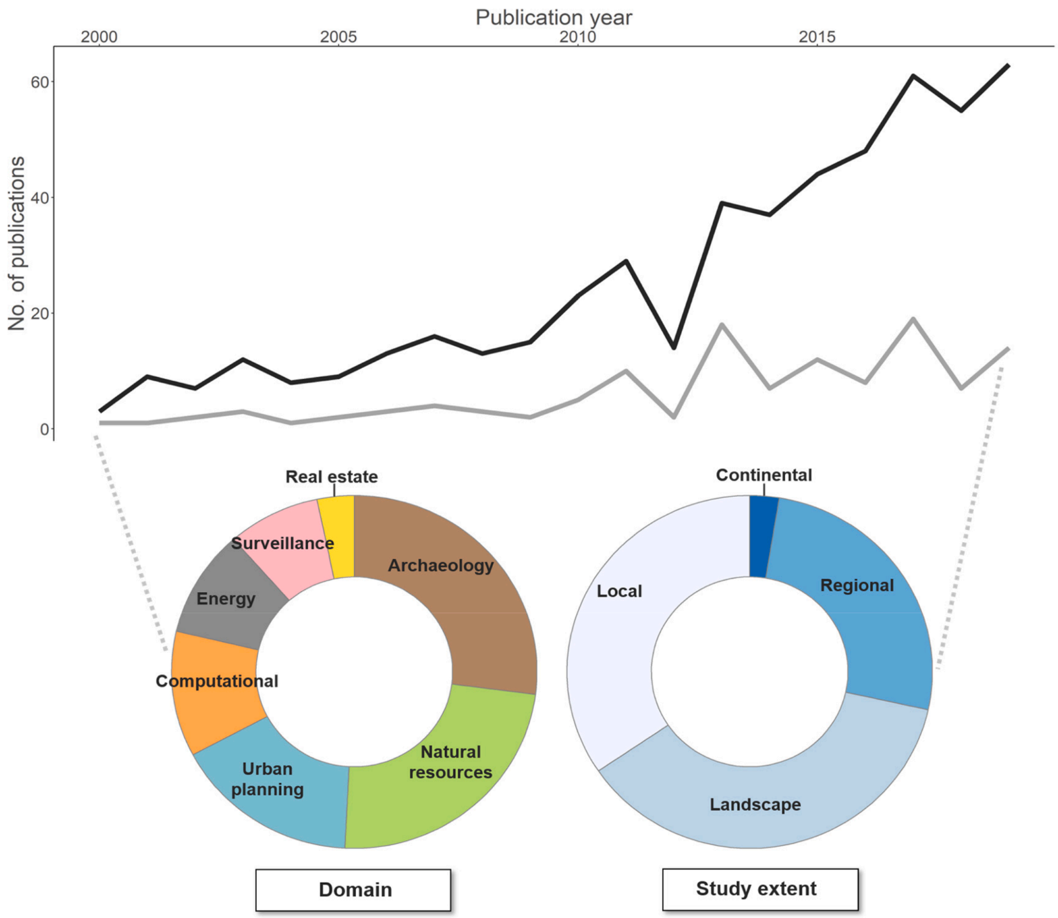

Fig. 2. Peer-reviewed academic papers published from 2000 to 2019 describing visibility or visual quality analysis. Web of Science search keywords included "viewshed," "viewscape," "line-of-sight AND GIS," and "visibility AND GIS." Of the 528 total papers found (black line), we selected one third (176) for in-depth review (gray line). The donut charts indicate the scientific disciplines represented and the spatial extents of the research articles selected for in-depth review.

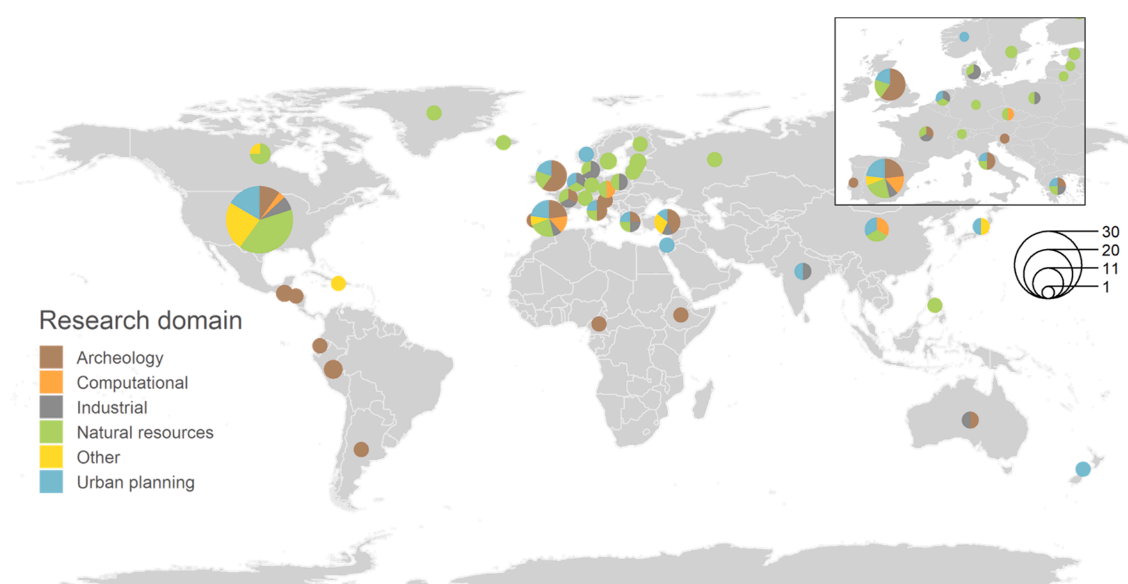

Fig. 3. Study location (by country) and disciplinary representation of 122 visibility and visual quality articles. Size of circles indicates the number of publications and the color indicates the proportion of total represented by each discipline.

studies.

Natural resource studies comprised the largest share of U.S. studies (12, 40% of U.S. studies). In Europe, natural resources publications were also common, but archaeology and urban planning studies were more dominant in Europe than in the United States (Fig. 3). Studies in Central and South America were almost exclusively archaeological, in which researchers recreated past viewsheds in order to understand or locate ancient ruins and understand human spatial patterns (Fig. 3). Urban planning and energy research was most commonly conducted in Europe (7, 23.3% of all urban planning studies; 8, 58.3% of energy studies; Fig. 3). Most computational studies (8, 57.1%) did not define a study region or used pseudo-data to test algorithms. Of the computational studies that had a defined study region, two were located in China and two in Spain, while the U.S. and Czech Republic had one each.

3.2. Data structures and viewshed computation methods

More than half of the 122 studies we reviewed used bare-earth digital elevation models (DEMs) (59.9%) while 21.3% used digital surface models (Fig. 4). Two studies used volumetric data structures, and three studies combined multiple data structures. DEMs were primarily derived from satellite sources (69.9% of articles using DEMs; Fig. 4), while most DSMs were derived from lidar sources (53.8% of DSM studies). lidar-based digital surface models to evaluate vegetation obstructions in viewsheds have increased 3-fold since 2000. Fifty studies computed viewsheds on elevation data of 10 m spatial resolution or finer (41%), compared to 35 studies that used coarser-grain elevation data (28.7%; Fig. 4). Urban planning studies rely more on fine grain, DSM data models (Fig. 5; 55% of urban planning studies). Archaeology studies are most likely to use medium-grain and fine-grain bare-earth DEMs (84.9% of archaeology studies; Fig. 5).

More than half (51.6%) of reviewed studies used the proprietary Viewshed tool in ESRI's ArcGIS software. Eleven percent of articles used open source software, while 8.1% created novel open source software or algorithms for the publication. <5% of studies combined multiple software types. As the number of publications increased over time, the proportion of software types remained steady.

More than half (52%) of studies did not report at least one of the following methods parameters: software, elevation data, spatial resolution or number of observation points used in viewshed calculation (Table 2).

3.3. Visual quality, weighting and human dimensions

More than half (53.3%) of the papers we reviewed did not assess visual quality, meaning their analysis focused solely on viewshed area or binary visibility (Fig. 6). For those studies that did assess visual quality, 52.6% focused on qualities of the built environment, 26.3% studied land cover, 12.3% terrain ruggedness and 8.8% greenness. Most studies that assessed visual quality were related to natural resources (26.3%), urban planning (22.8%) and archaeology (19.3%).

Most studies (54.9%) did not use viewshed weighting techniques, meaning the analysis considered all portions of the viewshed to be of equal importance. Of studies that did use weighting techniques, the most common was object or observer weighting (34 studies, 27.9%), which usually consisted of cumulative viewshed analysis that weights viewshed features by the number of points they're visible from. The next most common weighting technique was distance decay, also known as fuzzy viewsheds (16 studies, 13.1%). Archaeological studies were the most likely to use weighting (15 studies – 27.3 % of studies that used weighting and 45.5% of all archaeology studies), followed by urban planning (12 studies, 21.8% of weighted studies and 60% of urban planning studies). Natural resources studies were less likely to use weighting techniques (10 studies, 34.5% of natural resource studies).

Studies combining VVQ modeling with human dimensions accounted for 8.2% percent of the papers we reviewed (Fig. 6). Seventy percent of studies that used human dimensions were natural resources, while urban planning, energy and real estate each comprised 10% of human dimensions studies. In some publications (5; 50% of human dimensions publications), researchers asked human subjects to state visual preferences via surveys, most often relating to natural resources such as forested views, visibility of agriculture and wind turbine development. One article used participatory GIS, while four studies combined visibility analysis with social media data (Fig. 6).

4. Discussion

Visibility and visual quality (VVQ) analysis has a long history of use in a variety of scientific studies, from optimizing trade-offs in energy and urban development, to studying the patterns of movement and

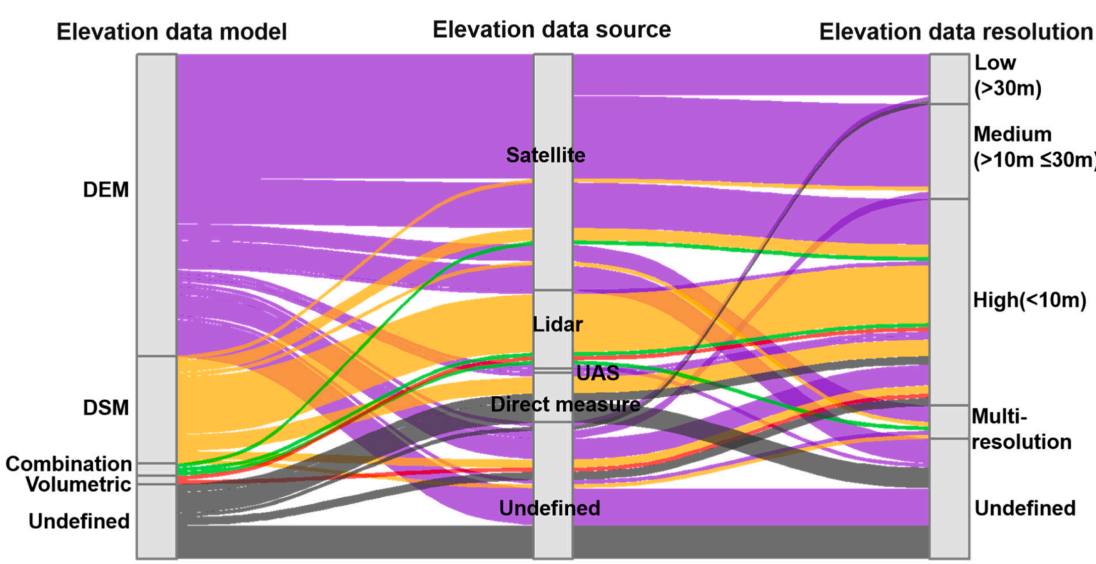

Fig. 4. Distribution and relationships among the elevation data models (left column), data sources (middle column) and spatial resolutions (right column) used in visibility models of 122 peer-reviewed studies. Each column consists of a stacked bar chart of the distribution of studies within that category, and each study is connected to its respective attributes by a ribbon. The ribbon's color indicates the elevation data model. For example, a study using high-resolution lidar-derived DSM will be represented by an orange ribbon flowing from left to right through the relevant attributes in each column.

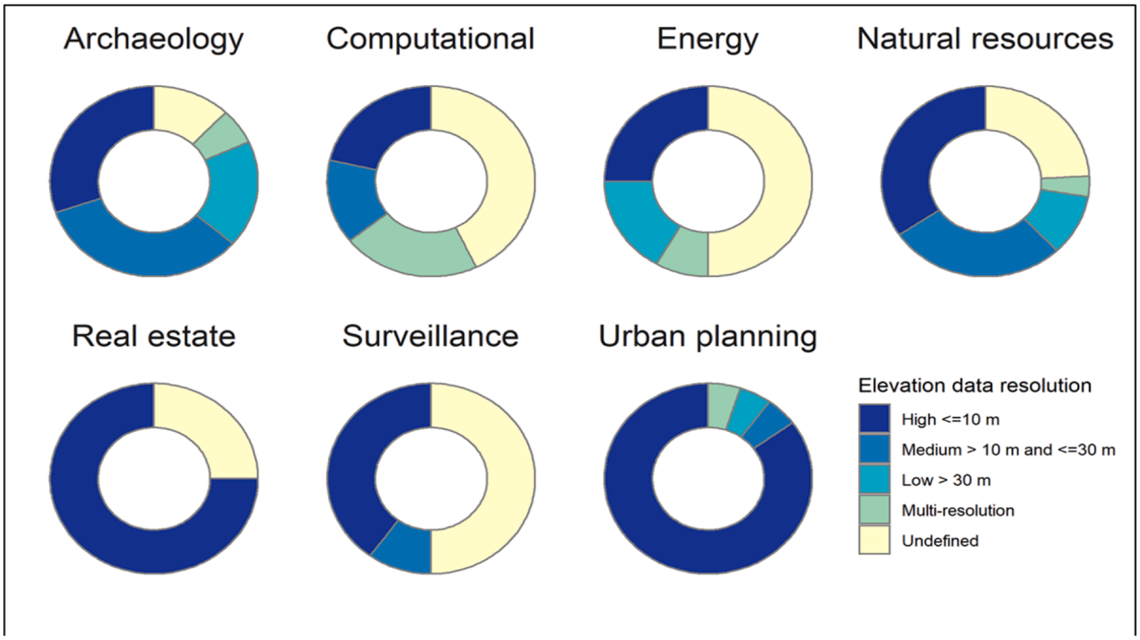

Fig. 5. Elevation data resolution used in visibility computation by disciplinary domain. The number of observer/observation points in each study ranged from 1 (10 studies) to as many as 4,000,000, with an overall median of 21.5. The number of observer points increased over time, with the median number of points used increasing 3.6-fold from 10 in the first 5 years of the study period to 36 the most recent 5 years.

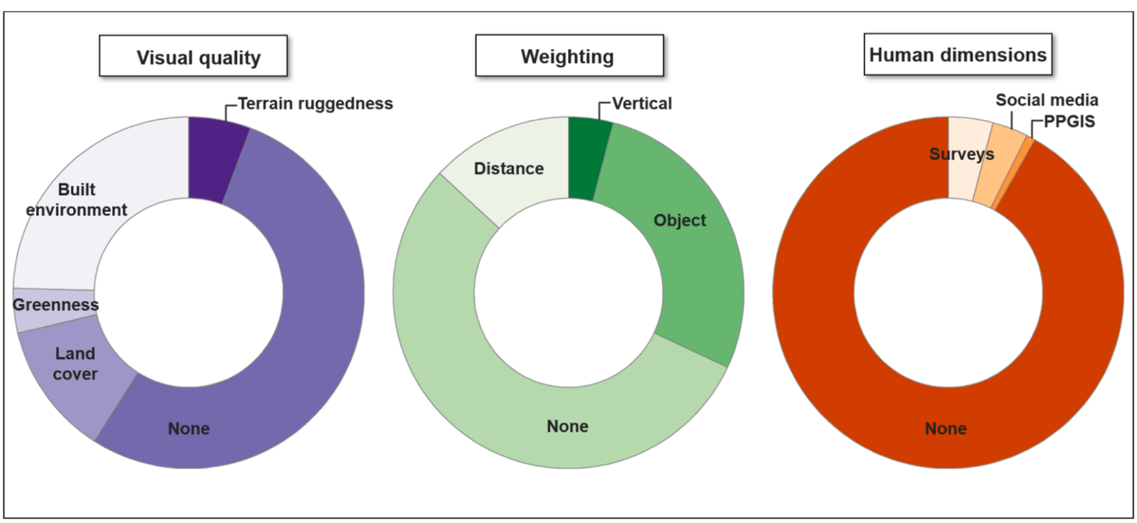

Fig. 6. Use of visual quality metrics, weighting techniques and human dimension methods in 122 peer-reviewed publications containing visibility analysis.

settlement in ancient civilizations, to conserving natural landscapes for their aesthetic value. Powered by rapidly advancing GIS-based computation, the cross-disciplinary nature of VVQ research benefits from a review to understand past uses, current trends and opportunities for collaboration and knowledge transfer. By systematically reviewing 176 recent peer-reviewed VVQ studies published from 2000 and 2019, we aimed to establish a base of knowledge from which researchers across scientific disciplines can draw insight and to inspire novel and forward-thinking applications of visibility analysis. Our findings delve into the conceptual and computational advances that are propelling VVQ research into the future and shed light on possible challenges and opportunities.

4.1. Geographic and disciplinary research trends

VVQ research applications varied by region, indicating that research questions reflect the terrain, economics and history of different countries. For example, in densely populated Europe, sustainable urban design and renewable energy appears to be the primary motivation of visibility studies (Fig. 3), while in the U.S. natural resource research in ecology and conservation dominate visibility research. In our database, VVQ research focused primarily on countries in the Global North (Fig. 3), and yet, resource extraction and human-driven land change disproportionately affects the developing world (Veltmeyer, 2013; Givens, Huang, & Jorgenson, 2019). This suggests the potential for underrepresentation of landscape visibility phenomena affecting the Global South. Notably, studies carried out in developing countries such as Guatemala, Ecuador, Peru, Cameroon and Haiti were conducted primarily by researchers based in foreign universities. There is a danger of research mirroring entrenched colonial patterns that have been identified in other domains such as field ecology (Baker, Eichhorn, & Griffiths, 2019) and medical trials (Benatar & Singer, 2000). Here, this phenomenon is compounded by opportunities to conduct visibility analysis without physically being present on the landscape. Future research could explore how the unequal distribution of environmental harms on the developing world manifests visually. Most of the VVQ research studies conducted in the Global South have been in the field of archaeology. Instead of focusing exclusively on the past, VVQ studies in the Global South that examine current and future viewsheds could facilitate a more comprehensive picture of landscape visibility in diverse cultural contexts around the globe. Because the visual connection to an environment is an inherently place-based human process, we encourage collaboration with local researchers or organizations to facilitate embedding research into the local knowledge base.

Our results indicate that different scientific disciplines utilize varying methods and study designs when modeling visibility, possibly because they analyze processes and patterns on different scales. For example, the smaller spatial extents of urban planning and transportation studies allows for finer-grain DSM data structures that delineate more detailed viewsheds. Because natural resources and archaeology studies covered larger spatial extents, coarse-grain elevation models were likely necessary to balance computational demands. Increasingly, methods used in urban planning studies to compute highly detailed and precise viewsheds are being scaled up (e.g. Labib, Huck, & Lindley, 2021) to cover larger extents. As computational barriers decrease, understanding how various disciplines apply VVQ methods will be important for scientific advances and inspiring novel applications in emerging fields.

4.2. Increasing computational efficiency and accuracy presents new opportunities, challenges

The 21-fold increase in VVQ-related studies (Fig. 2) coincides with the rise of accessible GIS software, both proprietary and open source (Knowles, 2008) and with the growth of computational power (Mack, 2011) and accessible public geospatial data (Coetzee, Ivánová, Mitasova, & Brovelli, 2020). Still, the database search also yielded several studies that did not use GIS tools specifically to conduct visibility analysis. Examples of other modeling methods include recording the maximum visibility of cameras (Ratcliffe, Taniguchi, & Taylor, 2009; Bao, Xiao, Lai, Zhang, & Kim, 2015) or directly measuring viewsheds by recording what human observers could see (Lang, Opaluch, & Sfinarolakis, 2014; Kamalipour & Dovey, 2019). While this indicates there are non-GIS methods that may be suitable for viewshed calculation, most of the studies we reviewed used GIS-based tools and are therefore the primary focus of our analysis.

Developments in line-of-sight algorithms (Zhu et al., 2019), computational power (Zhao et al., 2013), and elevation data (Carter, Shrestha, Tuell, Bloomquist, & Sartori, 2001; Liu, Zhang, Peterson, & Chandra, 2007) are continuing to advance efficiency, accuracy and precision of visibility models, opening up opportunities for deeper insight into the nuances of visual connection to the environment.

Commonly used viewshed algorithms include R3 (the “brute force” sequential approach: slowest and most accurate), line sweep (accurate, slower), R2 (increased speed by making estimations), XDraw (a faster, less accurate estimation than R2) (Franklin & Ray, 1994; Van Kreveld, 1996). Computational studies in our database largely fell into the following categories: improvements to the accuracy of the algorithms, computational speed improvements such as parallel processing, and increasing detail of underlying data models, made possible by the former two. A recently-published study presented an improvement to the XDraw algorithm, which increased accuracy by reducing distortion (Zhu et al., 2019). To increase speed, recent work has explored threading to graphical processing units (GPUs) with speed improvements up to 2,000x (Xia, Kuang, & Li, 2011; Zhao et al., 2013; Carter et al., 2019). A novel algorithm proved thousands of times faster without parallelization (Tabik, Zapata, & Romero, 2013), and block-partitioning was also found to speed up viewshed computation on large datasets (Jelinski & Wu, 1996). Combined with improvements to accuracy, faster computation provides substantial opportunity for larger spatial extents and detailed elevation models such as lidar-derived top-of-canopy surfaces, which require more computational power (Osterman et al., 2014; Anderson & Rex, 2019). These advances are also reflected in the number of vantage points used in viewshed calculations in the papers we reviewed, which enabled researchers to compute viewsheds for up to 4 million observer points. The four studies that used>100,000 vantage points were all published after 2013. A 2021 study not included in our database recently computed viewsheds at 5 m resolution for>86 million points in a high performance computing environment (Labib et al., 2021).

Advancements in the speed and accuracy of viewshed algorithms, combined with parallel processing techniques, enables use of higher resolution, more realistic elevation data structures. Increasing coverage of aerial lidar surveys around the globe has further enabled the use of these types of data models, as evidenced by the 3-fold increase in the use of lidar-derived DSMs throughout the study period. As elevation data source and model type are correlated with resolution (Fig. 4), viewsheds are calculated with increasing spatial detail. However, when computing viewsheds on raster-based elevation surfaces, a single cell can only represent one elevation point. In some studies we reviewed, these gridded elevation models were referred to as 2.5D, because with one elevation value per cell, two objects cannot exist in the same place at different heights (Bishop, 2003; Jung, Olsen, Hurwitz, Kashani, & Buker, 2018). This makes it impossible for observers in 2.5D to “see” underneath an object that doesn’t extend all the way to the ground. Computer graphics technology is enabling researchers to compute viewsheds in true 3D space utilizing a computer’s GPUs, presenting a promising avenue for producing accurate and detailed viewshed models. Studies we reviewed use graphics software to compute visibility of potential wind turbines (Wróżyński, Sojka, & Pyszny, 2016; Rafiee, Van der Male, Dias, & Scholten, 2018), and in a voxel-based volumetric model of urban structures (Fisher-Gewirtzman, Shashkov, & Doytsher, 2013).

Still, DEM models of medium (10 to 30 m) resolution remained overwhelmingly the primary data model for visibility analysis (60.5%, Fig. 4), despite the fact that bare earth elevation models are known to overestimate viewshed size and resulting visual quality metrics (Vukomanovic et al., 2018). The accuracy of a viewshed depends on the detail of the input data, and when considering binary visibility, as 52.4% of studies in our database did, a viewshed error can mean the difference between a 0 and a 1 (Klouček, Lagner, & Šímová, 2015). The persistence of coarse- and medium- grain elevation models in VVQ literature indicates barriers still exist that encumber the application of more detailed and accurate tools. One important barrier may be the lack of consistent reporting of methods. About a quarter of papers we reviewed did not report the elevation data structure, sources, spatial resolution, software or other key information for reproducing methods. This could cause subsequent research to duplicate efforts or miss important advancements within their discipline. Likewise, several studies we reviewed presented novel algorithms for viewshed computation, however they did not make the associated code or software readily available or accessible. There were some notable exceptions however (e.g. Osterman 2014; Carter 2019), indicating that advancements are being implemented in both open source and proprietary software enabling more widespread use.

As it is the most widely used option for researchers, advances in ESRI’s ArcGIS Viewshed tool are likely to have substantial impact on the field. In 2014 ESRI first released the Viewshed 2 tool: a GPU-enabled visibility algorithm that calculates viewsheds in 3D space and has the option of computing viewsheds for all possible sightlines (more accurate) or via perimeter sightlines (faster, estimated) (ESRI 2021). The recent integration of voxel data structures into ESRI products are promising for the advancement of more accurate viewshed models calculated in true 3D space (Angel, 2020).

As advances continue to emerge and are incorporated into commonly used software, it’s important for researchers in all disciplines conducting

VVQ research to consider the tradeoffs in viewshed algorithms and elevation data structures as they relate to their specific research question. For example, if only computing visibility from a handful of points and accuracy is important, a slower process that analyzes every possible sightline would suffice. When using faster algorithms that estimate viewshed boundaries, the detail of the underlying data may play an important role when considering trade-offs in processing time and accuracy. In deserts, bare-earth DEMs may be appropriate at landscape extents, while in forested areas, top-of-canopy models have a substantial effect on results (Vukomanovic et al., 2018). When human safety is at stake, such as in the case of transportation research, true 3D representations and the most accurate computational tools are imperative (Jung et al., 2018). Thus, we encourage our colleagues not to use the same black-box algorithms and elevation data structures simply because they have long been the defaults in their disciplines. New developments in algorithms that leverage parallel processing, GPUs and game engine software can significantly expand the detail, spatial extent and accuracy of visibility modeling in the future.

4.3. Visual quality and human dimensions: Beyond the viewshed

The increasing accessibility of numerous, detailed viewsheds at larger extents and finer grains carries the possibility of engaging in "technological determinism" by allowing data availability and computational capacity to drive research questions (Déderix, 2019). Some archaeological research articles have urged their colleagues to avoid "merely building a huge but futile corpus of visibility data" (Déderix, 2019) and warn against conflating visibility with perception (Gillings & Wheatley, 2001). These archaeologists make a crucial point: a viewshed is not experienced uniformly. How humans perceive depends on where an object is in their visual field, what that object is in front of or next to, the observer's cultural history and sense of place, and individual preferences. A wide variety of metrics and methods exist in our review that highlight the potential to better represent the dynamic, personal experience of visual connection with a landscape.

We found that viewshed weighting methods were used in a variety of applications to go beyond the binary visible/non-visible modeling approach and better represent the dynamic ways that observers experience landscapes. The most common format we encountered in our review was cumulative viewsheds, which count the number of times a given landscape pixel is "seen" from multiple observer points, resulting in a surface that reflects which parts of the viewshed are most commonly visible (e.g. Tabik et al., 2013; Wright, MacEachern, & Lee, 2014; O'Driscoll, 2017). We also reviewed several studies that used fuzzy viewsheds, also known as "Higuchi viewsheds," that assign smaller coefficients to elements further away to account for how humans prioritize elements closer to them in their visual field (Ruestes, 2008; Fernandez-Jimenez et al., 2015; Guiducci & Burke, 2016).

Measuring visual quality is another avenue for exploring the content of a viewshed. Metrics of visual quality have been used throughout VVQ literature to represent landscape attributes through visual concepts (Tveit, Ode, & Fry, 2006),and connect these concepts to measurable indicators to help quantify visual character (Ode, Tveit, & Fry, 2008). Most of the studies we reviewed that went beyond binary visibility to explore visual quality metrics were urban planning or energy research that measured the presence of built structures. Land cover was the dominant visual quality studied in natural resources research. One of the most detailed visual quality studies we reviewed used 23 metrics, including patch and species diversity indices, terrain complexity, land cover proportions and presence of historical sites (Tenerelli, Püffel, & Luque, 2017). Visual quality metrics like greenness, land cover and historical sites were also used to study the social inequities in urban views (Yasumoto, Jones, Nakaya, & Yano, 2011). For these types of studies, we suggest the use of the word 'viewscape' to represent how the contents of the visible area—not just its boundaries—are relevant to the connection between observer and landscape (Vukomanovic et al., 2018).

While these visual quality studies focused on how viewscapes vary across space, less attention was paid to temporal heterogeneity. One study argued that viewshed computation by point alone is not sufficient to represent the dynamic nature of visibility and presented a method to quantifying viewshed corridors via multiple sequences of points that better represents the experience of moving through a landscape (Chamberlain, Meitner, & Ballinger, 2015). Only one publication we reviewed modeled the contents of a viewshed changing over longer periods of time: studying the cumulative visual effects of windmill development for 3 9-year periods between 1982 and 2007 (Möller, 2010). There remains substantial opportunity to leverage computational advances that allow for more numerous and detailed viewsheds to better quantify both the spatial and temporal dynamics of visual experience (Ode et al., 2008).

While visual connection to a landscape is known to be both an individual and social process (Kandel et al., 2000; Nijhuis et al. 2011), studies that connect VVQ analysis to human dimensions via revealed or stated preferences or participatory mapping were rare in our database. The lone publication we reviewed that used participatory mapping (PPGIS) techniques asked respondents to map parts of the landscape they valued most (Garcia-Martin et al., 2017), highlighting how people valued highly visible and aesthetic parts of the landscape. Two studies we reviewed approached viewshed valuation by assessing willingness to pay for specific views, via surveys (Mueller, Springer, & Lima, 2018) and hedonic models (Hamilton & Morgan, 2010). All four studies that used social media data were in the natural resources domain and relied on the photo-sharing platforms Panoramio and Flickr. Substantial opportunity exists in combining VVQ research with human subjects and qualitative methods. Participatory GIS and tangible interfaces can allow researchers insight into stakeholder preferences (Garcia-Martin et al., 2017; Petrasova, Harmon, Petras, Tabrizian, & Mitasova, 2018) while personalizing connections to problems and their solutions through visualizations of place (Vukomanovic, Skrip, & Meentemeyer, 2019). Direct surveys using photos or videos (Bishop, 2003) can also help draw tighter connections between human processes and computed visibility. Potential lies in mining the troves of social media data (Yan et al., 2017), or drawing from the cognitive sciences by using mobile fitness tracking devices and other wearable technologies for measuring human response to their environment (Millar et al., 2021).

4.4. Current trends and future opportunities

Our search unearthed some novel applications that may expand how we define VVQ research in the future. A study of the visibility of people smoking outdoors (Pearson, Nutsford, & Thomson, 2014) for example suggests that there are valuable public health applications that could be included in conversations about VVQ research advances. The studies we reviewed reflect another important aspect of viewsheds: humans are not the only animals that can see. For example, one study modeled quail responses to visible fracking wells (Duquette, Davis, Fuhlendorf, & Elmore, 2019), while another devised a habitat suitability model for bighorn sheep (Johnson & Swift, 2000); both powered by fine-grain lidar-derived elevation surfaces, which are important for leveraging viewsheds in ecology (Aben et al., 2018). In these studies, viewshed computations were adjusted for the known biological specifications of the animal. We also noted several studies that use line-of-sight analysis for modeling something other than sight, such as several studies that explored the optimization of satellite and communication infrastructure coverage (Etherington & Alexander, 2008; Wang, Groves, & Ziebart, 2012; Ghosh, Ghose, & Mohanta, 2013). These non-traditional uses suggest that advancements in VVQ modeling could support a variety of promising applications beyond the human visual field.

The three most recent years of publications we reviewed (2016–2019) reveal some novel applications and methods that may be signposts for where VVQ research is headed in the future. Multiple recent studies explored improvements to computationally efficient representations of 3D landscapes and built features. Two 2019 studies leveraged the "multi-patch" data structure (Stewart, 2019; González-Gómez & Castro, 2019), which computes a true 3D viewshed where sightlines can extend underneath features that do not extend all the way to the ground. We also found mixed data model approaches, such as including lidar-based top-of-canopy "curtain" around a scenic byway but a bare-earth DEM for the rest of the elevation survey (Anderson & Rex, 2019). This increases viewshed accuracy while minimizing sacrifices to efficiency. Another study assessed the sensitivity of a viewshed model to data resolution and used fine grains where most important (Palmer, 2019); a promising foray into exploring tradeoffs of efficiency and detail in VVQ analysis. Viewshed algorithms have also recently been applied in optimization studies, such as for placement of surveillance equipment (Yilmaz & Gencer, 2018) or for fire watch tower placement (Sakellariou, Samara, Tampekis, Christopoulou, & Sfougaris, 2017). Notably, VVQ methods are becoming more common in real estate research; all four real estate studies in our database were published after 2010. This could be due to increased amenity-driven development in the post-recession real estate boom (U.S. Census Bureau, 2021) combined with increased lidar coverage of coastlines, cities and other landscapes relevant to housing development.

The systematic approach and sampling method used enabled the authors to capture VVQ methods and research trends in detail and depth. While this analysis likely captures common research trends and some emerging themes across 122 peer-reviewed studies, it is not comprehensive, so some novel developments may not have been included in this review. Not all publications are indexed in the Web of Science database and of those indexed we reviewed one third in depth. We also limited our search to articles published in English thus excluding findings published in languages other than English. In addition, cutting-edge work is not always published in peer-reviewed journals, and our search excluded conference proceedings, which constitute an important outlet for fields such as computer science. Future work that comprehensively reviews the most recent developments could shed additional light on technological advances, novel methods and influential results. Still, we believe that this is a robust study that systematically examines the use of visibility modeling across a wide range of disciplines and applications.

5. The Four R's: A framework for planning and writing future VVQ studies

Moving forward, it will be vital to encourage consistent use of terms, to think critically about study designs, to compare and validate algorithms in a variety of landscapes, and to cultivate open science practices to improve reproducibility and prevent researchers from reinventing the wheel. Such measures would facilitate the use of accurate and precise VVQ modeling methods across disciplines. To help achieve these goals, we drew from the findings of this review to synthesize a set of suggested steps for researchers and we organized those steps in a four-level framework. Each level requires increasing amounts of friction to implement, but these levels build upon each other to address some of the opportunities identified in this review (Fig. 7). This framework and the preceding analysis can be used as guidelines for VVQ researchers to encourage consistency and rigor, challenge norms and expand research horizons as the field continues to advance.

Level 1: Report methods comprehensively for reproducibility and rigor.

To ensure reproducibility and rigor, include explicit reporting of methods, data and software used in the analysis (Table 3). Share open source code in online repositories where appropriate.

Level 2: Re-evaluate algorithms and data sources.

Know your algorithm. If using existing software, consider what type

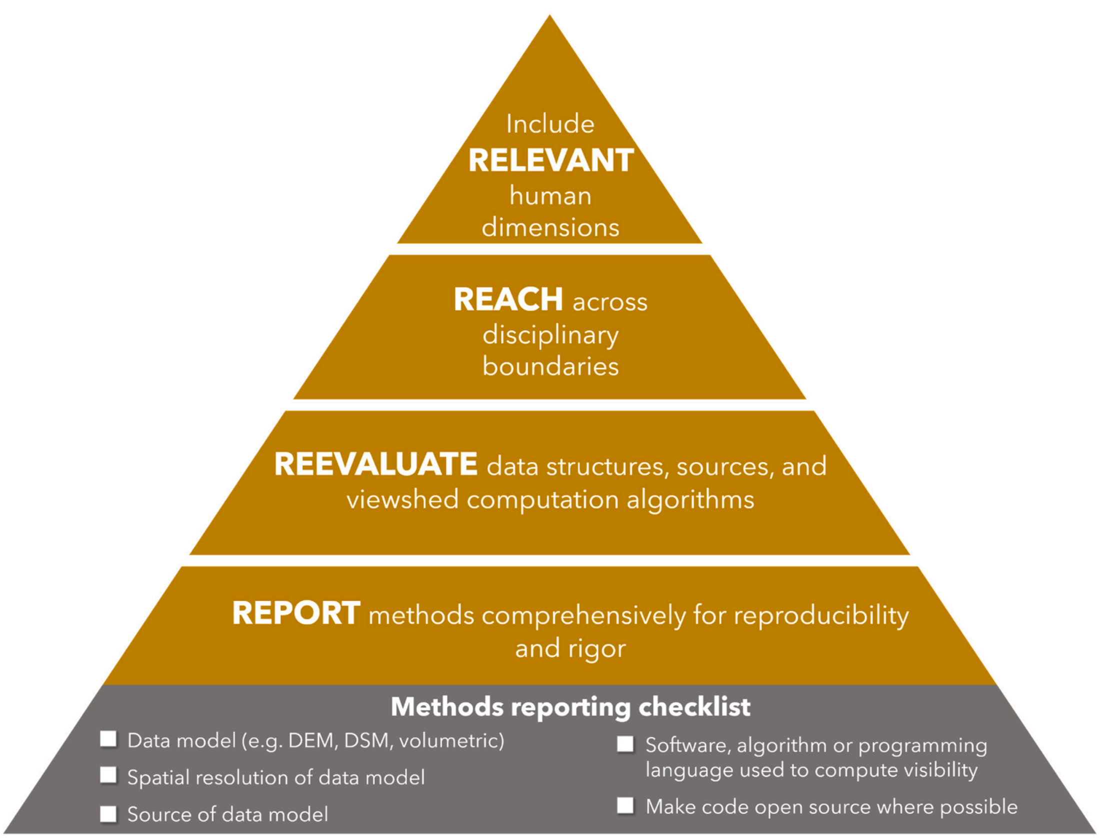

Fig. 7. The Four R's: A suggested framework for reporting and planning future visibility research to efficiently build on previous work, encourage interdisciplinary applications and support reproducibility and rigor.

of algorithm is used and how its accuracy fits in the context of your study area and research questions. Consider which data structure is most appropriate to best represent specific landscape characteristics. Where needed, combine data sources to balance computational cost with data structure representativeness (e.g. multi-resolution or DEM/DSM combinations).

Level 3: Reach across disciplinary boundaries.

Additional domain expertise may help support the appropriate methods and data structures identified in Level 2. Building bridges across disciplines will help promote the use of advanced visibility modeling techniques (e.g. game engine technology, high performance computing) to meet the needs of specific research questions. Collaborate with experts on the people (or animals) whose viewsheds are being modeled for robust interpretation and context.

Level 4: Include Relevant human dimensions.

Leveraging the collaborations emphasized in Level 3, incorporate direct human dimensions such as surveys, participatory mapping and modeling, social media data or physiological measurements.

6. Conclusion

This study offers the first known multidisciplinary systematic review of visibility and visual quality research. From the total 528 peer-reviewed publications our search produced, an in-depth review of 176 studies yielded insight into the diverse assemblage of research that leverages VVQ methods. Our analysis highlights several trends and opportunities. First, VVQ research increased 21-fold over the past 20 years. Research was primarily in the fields of archaeology and natural resources and was conducted predominantly in the Global North, suggesting ample opportunities for future visual quality work in other disciplines and locations. Second, viewsheds were computed most commonly using bare-earth digital elevation models with proprietary software. However, there is increasing use of high-resolution digital surface models and 3D features leveraging computational advancements that are increasingly available via open source and proprietary software. And third, studies that combine visibility analysis with human dimensions remain rare, and visual quality and weighting methods may be siloed by discipline. As technological advances allow for more efficient, accurate and numerous viewshed computation, it's important to cultivate a centralized knowledge base of VVQ methods, trends, research gaps and advancements. While researchers from different disciplines have different needs, the GIS-driven technology behind viewshed computation remains a common thread. We hope that this analysis helps facilitate the application of such techniques across disciplines.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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