Introducing visual neighbourhood configurations for total viewsheds

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Abstract:

The Visual Neighbourhood Configurations (VNCs) approach is presented: a new approach for exploring complex theories of visual phenomena in landscapes by processing total viewsheds. Such theories most commonly concern the configuration of visual properties of areas around locations rather than solely the visual properties of the locations themselves. The typical approach to interpreting total viewshed results by classifying cell values is therefore problematic because it does not take cells' local areas into account. VNC overcomes this issue by enabling one to formally describe area-related aspects of the visibility theory, because it formally incorporates the area around a given viewpoint: the shape and size of neighbourhoods as well as, where relevant, the structure and expectation of visual property values within the neighbourhood. Following a brief review that serves to place the notion of the VNC in context, the method to derive visual neighbourhood configurations is explained as well as the *VNC analysis tool* software created to implement it. The use of the method is then illustrated through

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a case-study of seclusion, hiding and hunting locales afforded by the standing stone settings of Exmoor (United Kingdom).

Keywords: GIS, landscape archaeology, visibility, total viewsheds, visualscapes, affordance viewsheds, neighbourhood analysis.

Highlights:

- A new approach is presented for the formal representation and evaluation of complex visibility theories
- The Visual Neighbourhood Configurations (VNC) approach represents the distribution of visual properties in a small area as specified by an archaeological theory
- Total viewsheds are taken as input to the approach and are formally compared against the VNC representing the archaeological theory
- A software tool has been developed to implement VNCs with a wide range of analytical techniques
- VNCs represent a step towards more complex theoretical formal visibility studies

1. Introduction

Total viewsheds offer a representation of the visual properties inherent in a landscape based on its topography and are generated by adding up viewsheds generated from all cells (taken to represent possible viewpoint locations) in a digital elevation model (DEM) (Llobera 2003; Llobera et al. 2010). The archaeological potential of such analyses has been apparent since the late 1990s (e.g. Lake et al 1998), but this potential has rarely been explored due to two main issues: computation time and the tendency to use these summed viewsheds to study a very limited set of hypotheses. The first issue has now been all but overcome. Computing technology and open-source software that enable the creation of total viewsheds on acceptable spatial resolutions within realistic timeframes are commonly available (e.g. Čučković 2016). The second issue refers to the fact that the vast majority of GIS-based visibility studies in archaeology concern a calculation of the area visible from a single discrete point or set of such points in a landscape, rather than formally incorporating the area around a given viewpoint or even the study area as a whole. This effectively means that we are tied to exploring only one among a vast number of ways in which visibility could have structured space and affected past human behaviour. The latter issue is being addressed through an increasing number of applications of GIS-based visibility analyses that explicitly set out to represent and explore

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more diverse archaeological hypotheses. Most notable among these are the concepts of the visualscape and affordance viewshed, which share a focus on the use of GIS approaches as heuristic tools to study human practices and meanings (e.g. Gillings 2009; 2012; Llobera 1996; Llobera 2003). In practice these concepts have been used to foreground and explore the inherent relationality of acts of looking and seeing (e.g. affordance viewsheds) as well as study the complete set of ways in which visual properties structure environments and how this affects animal behaviour, most notably humans (e.g. the visualscape). Whilst a number of GIS-based techniques and applications have been developed to operationalize these concepts, or variants of them, for exploring different hypotheses (e.g. Eve and Crema 2014; Gillings 2015a; Paliou et al. 2011; Wernke et al. 2017) these all share a focus on comparing the visual properties of *specific locations* rather than locations within their local area setting (with the notable exception of visual prominence (Llobera 2003) which takes an explicitly neighbourhood-based approach).

In this paper we seek to address precisely this issue of discrete viewpoint location through what we have termed Visual Neighbourhood Configurations (VNCs). These offer a representation of hypothesised patterns of the visual structure within an area immediately surrounding a location in the landscape. Following a brief review that serves to place the notion of the VNC in context, the method to derive visual neighbourhood configurations is explained as well as the *VNC analysis tool* software created to implement it (Garderen 2017). The use of the method is then illustrated by revisiting and elaborating on Gillings' (2015a) study of seclusion, hiding and hunting locales afforded by the standing stone settings of Exmoor (United Kingdom).

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2. Background

In recent years, the more theoretically informed GIS-based analysis of the visual properties of landscapes and how they might have affected past human behaviour has focused on the study of entire landscapes. There are many terms for the body of techniques to perform such analyses: visibility fields (Eve and Crema 2014), affordance-viewsheds (Gillings 2009), complete-cumulative viewshed analysis (Lake et al. 1998), visualscapes (Llobera 2003), and total/inherent viewsheds (Llobera et al. 2010) to name but a few (Gillings 2017: 122-123).

Perhaps the most ambitious of these has been Llobera's notion of the visualscape as "the spatial representation of any visual property generated by, or associated with, a spatial configuration" (2003, 30). It is a purposefully abstract and generic definition that aims to provide an umbrella term for approaches that seek to study the visual structure inherent in an environment. In contrast, affordance viewsheds are more targeted, stressing the way in which specific visual dispositions (e.g. exposure, concealment, surveillance) only emerge relationally, through specific human-landscape engagements. Rather than latent or inherent, the specific visual properties of a location “manifest themselves in the context of this specific activity and assemblage of actants; the same location may afford very different properties to individuals or animals bound up in other tasks and doings” (Gillings 2015a, 2).

Despite differences in their respective heuristic ambitions and the assumptions that underlie them, with the exception of Llobera’s method for visual prominence, the techniques operationalising these concepts have focused heavily on the study of the visual properties of discrete locations rather than how these properties are related to those of locations in their immediate vicinity. This is evident in the way in which the results of viewsheds are most commonly discussed: e.g. location X is visible from n other locations. Total viewshed results are likewise explored by identifying blocks of discrete locations with high or low visibility, and by counting the number of features of research interest (usually humanly-made structures) located in these areas. This approach is very sensitive to the specific viewshed results at the locations of research interest and in archaeological visibility studies these locations are often partly arbitrary: a specific point location is selected to represent a human-made feature, coinciding with a specific cell on the raster DEM used. This approach is used despite it being limited by a number of assumptions that are commonly formulated in such studies: the human-made feature is larger than this cell; an observer would be able to move outside the area of the cell to observe from different vantage points; the observer has experience and knowledge of the visual properties of a larger area. The total viewshed results for this cell will also be highly sensitive to the elevation value of the cell in the DEM and those of the cells immediately surrounding it. This issue is recognised and is often addressed by representing human-made features as polygons, such as the boundaries of a site extent, or by qualitatively interpreting the viewshed result of locations of research interest alongside those immediately surrounding it. Looking at the latter, it is notable how often it is the wider spatial context that is emphasised. For example, viewpoints are said to occupy highly visible parts of the landscape or are said to have been placed in areas that offered expansive views.

This paper proposes a method for incorporating the broader area around a given viewpoint formally. This method has the benefits of (1) being able to express a more diverse range of spatial configurations that capture hypothesised ways in which the relationship between a

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location and its immediate surroundings matter with respect to their visual properties, and (2) allowing modification and refining of the variables used to express these configurations in a formal and controllable way. It achieves this by illustrating a systematic application of the visualscape and affordance-viewshed concepts by formally representing and exploring a wide range of hypotheses concerning the structuring of space through visual patterning and how this affected past human behaviour. In addition, it significantly expands the toolkit operationalising these concepts through the proposal of what is termed the VNC approach.

3. Method: Visual Neighbourhood Configurations

3.1. Intuition

As noted, viewshed results are most commonly interpreted on a location by location basis through a qualitative comparison of the results of individual locations with those in their immediate surroundings. Whilst the visual envelope of a single dwelling may be deemed significant (e.g. Bender et al. 2007, 51-53) more often it is the visual properties of the area surrounding a specific location that are more relevant to an archaeological theory than those of the location itself. If one assumes, for example, that settlements are preferentially located in parts of the landscape which are highly visible, it is not necessarily the visibility of the exact location of the settlement that is important, but rather the overall visibility of the area in which it is embedded.

We propose Visual Neighbourhood Configurations (VNCs) as an approach to formally expressing hypotheses about the way in which a particular visual property structures space in a small area. A VNC specifies the size and shape of the surrounding area (i.e. the neighbourhood) that is taken into account when analysing a specific location. A structure, subdividing the neighbourhood into smaller areas for which different visual properties are assumed, and expected visual property values for specific locations within the neighbourhood can also be incorporated in the VNC to explore more complex assumptions. Subsequently a total viewshed of the study area can be analysed with respect to the VNC, computing for each location a value that reflects the visual properties of the neighbourhood (see Figure 4 for an example of the VNC analysis process). Archaeological assumptions can then be evaluated by comparing the resulting values of the locations of known settlements or other archaeological features to those in areas where no such features are located.

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Consider for example the assumption that settlements are located in areas that are not very visible, but close to areas that are highly visible. A VNC can be created that expresses this spatial distribution of low visibility directly surrounding a focal location and higher visibility in areas close by. Analysing a total viewshed with respect to this VNC reveals for each location how well it fits that assumption. This result can be used to evaluate whether settlements are indeed found in locations that fit the assumption better than other locations.

3.2. Definition

A Visual Neighbourhood Configuration (VNC) defines which locations l_i belong to the neighbourhood $N_f = \{l_1, \dots, l_n\}$ of a focal location l_f. In addition to the *shape* and *size* of the neighbourhood, the VNC also specifies a *structure*: a subdivision of the neighbourhood in multiple areas or *groups* for which different visual properties are assumed. Depending on the evaluation method used (see Section 3.3), *expectation values* may be specified for each of the groups.

Size: the size of the area around a focal cell that is relevant to the theory being explored. The selection of an appropriate neighbourhood size depends entirely on the researcher's theoretical assumptions. It is often useful to explore a range of different sizes in order to examine the sensitivity of the results to changing neighbourhood size.

Shape: in theory, any subset of cells around a focal location can be defined as the neighbourhood, so a neighbourhood can have any desired shape. However, since assumptions about visibility often concern an area within a certain distance from the focal location, a circle around a focal location is the most straightforward and intuitive shape. The radius of the circle in that case expresses the size of the neighbourhood.

Structure: the neighbourhood contains all locations that are considered relevant to the focal location, but they may not all play the same role in the archaeological assumption that is being expressed. The VNC can therefore contain different subgroups of locations for which different visual properties are expected. The simplest structure is a uniform VNC, as shown in Figure 1a. Alternatively, one can specify distance bands (Fig. 1b), a gradual increase or decrease of visibility with increasing distance from the focal location (Fig. 1c), or wedges in different directions from the focal location (Fig. 1d).

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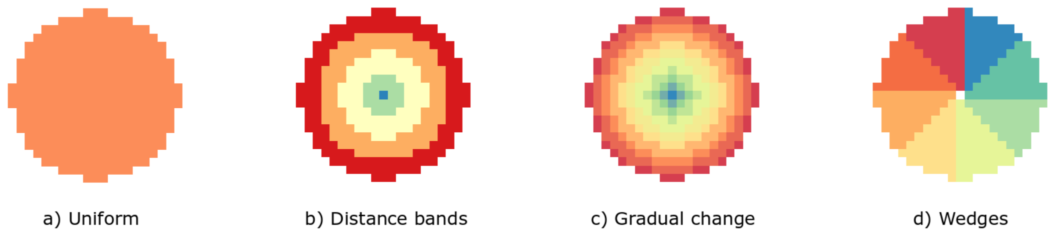

Fig. 1. Example representations of VNCs with different structures where groups of cells are indicated by different colours: an assumption about the visual property values is formulated for each group of cells.

Expectation values: to express the different visual properties assumed for the different groups in the VNC structure, an expectation value can be assigned to each group. In the expectation-based evaluation methods (see Section 3.3), each cell in the actual neighbourhood of a focal location is then compared to this hypothesized value to compute how well the location matches the assumption expressed by the VNC with expectation values. Expectations should be expressed on a scale from 0 to 1, where 0 corresponds to the lowest visual property value occurring in the study area, and 1 corresponds to the highest visual property value.

Various (archaeological) assumptions about the way in which visibility structured (or might have structured) a given space can be expressed in terms of a VNC. The expression and testing of hypotheses in this way forms the focus of the approach presented here.

As an example, consider the assumption that tombs or rock-art sites were located in places that are themselves invisible or visually unimpressive but within short distance of visually striking or distinctive locales. This hypothesis can be expressed as a VNC as shown in Figure 2. The neighbourhood radius is set to 100 m, with a structure consisting of two distance bands around the focal location l_f. An expectation value of 0 (the lowest visual property value) is assigned to the focal cell and distance band A (locations within 50 m from l_f), corresponding to the assumption that the site location and its immediate surroundings have low visibility. The assumption that there are locations with high visibility within short distance of the site location is expressed by assigning an expectation of 1 (the highest visual property value) to distance band B (locations 50-100 m removed from l_f).

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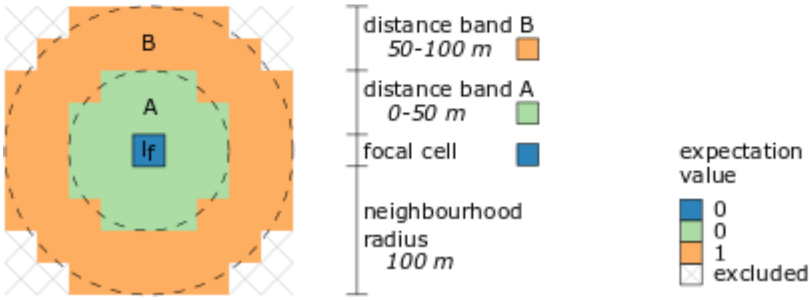

Fig. 2. VNC of an example hypothesis where archaeological features are located in invisible places surrounded by highly visible locations. This can be expressed by considering a low expectation value for distance band A and a high one for band B.

It should be clear from this example that the visual neighbourhood configuration is an expression of the extreme state of an assumption. The hypothesis can now be evaluated by computing for each location in the study area how well it fits this assumption. The evaluation method (RMSE, see Section 3.3 for details) assigns each location a value between 0 and 1, where 1 represents a perfect fit to the configuration and 0 represents the exact opposite of the configuration (i.e. the lowest visual property values where there should be the highest). Based on this result one can check whether known tombs and rock-art sites are indeed located in areas that fit the assumption better than other locations.

A key benefit of using VNCs is that the expectations following from our hypotheses of the way visibility structures space are formally expressed. This technique therefore lends itself very well to hypothesis testing and scholarly communication of complex theories: what spatial distribution of a visual property do we expect to see if the hypothesis is true, what do we expect if it is the exact opposite, and how do these compare with the actual distribution? Although the use of formal expressions of hypotheses has great potential, it is not yet common practice in GIS-based visibility studies in archaeology (for notable exceptions see Wheatley 1995; 1996; Fisher et al. 1997; Lake and Woodman 2003; Llobera 2007; Lake and Ortega 2013; Eve and Crema 2014; Gillings 2009; 2015a).

3.3. Evaluation methods

VNCs can be operationalized by using one of the following methods to evaluate the neighbourhood of each cell in the study area. All evaluation methods return a raster where each cell location l_i has the value computed for the neighbourhood with l_i as the focal location. Archaeological assumptions can then be evaluated by comparing these output values of locations of sites or other archaeological features with the values in areas where no sites are located.

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The computations and interpretations of values in this section are based on the assumption that the input total viewshed raster is normalized, containing only values between 0 and 1. The visual property values are normalized by mapping the highest value occurring in the study area to 1, and the lowest value occurring in the study area to 0. The intermediate values are scaled to this range. For focal locations close to the border of the study area some cells of the neighbourhood might fall outside of the study area, as illustrated in Figure 3. Such focal locations close to the borders will be ignored in the computations: similar to total viewshed calculation, in order to avoid edge effects one needs to extend the study area for which representative analysis results need to be obtained by a distance equal to the radius of the VNC. The input total viewshed should therefore equal the size of the study area extended by the radius of the VNC.

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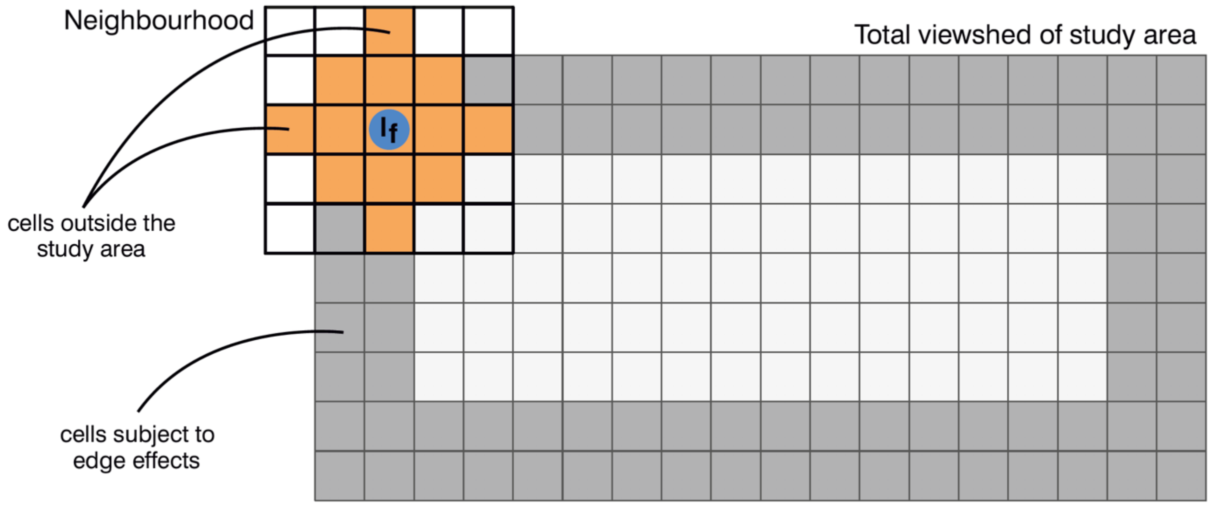

Fig. 3. Example of a cell whose neighbourhood extends beyond the input total viewshed defining the study area. When interpreting VNC analysis results, such cells should be excluded to remove edge-effects.

Average visibility: perhaps the simplest assumption to test is that the visibility in the neighbourhood is high or low. This assumption can be checked by computing the average visual property V_{avg} of each focal location l_f, which is defined as the mean of all visual property values in the neighbourhood:

$$V_{avg}(l_f) = \sum_{l_i \in N_f} \frac{v(l_i)}{|N_f|}$$

Where $N_f = \{l_0, \ldots, l_n\}$ is the neighbourhood of focal location l_f and $v(l_i) \in [0,1]$ is the normalized visual property value of cell l_i. The resulting value indicates whether a location is positioned in an area of very high visibility (values close to 1) or in an area of very low visibility (values close to 0) (see Figure 4 for an example).

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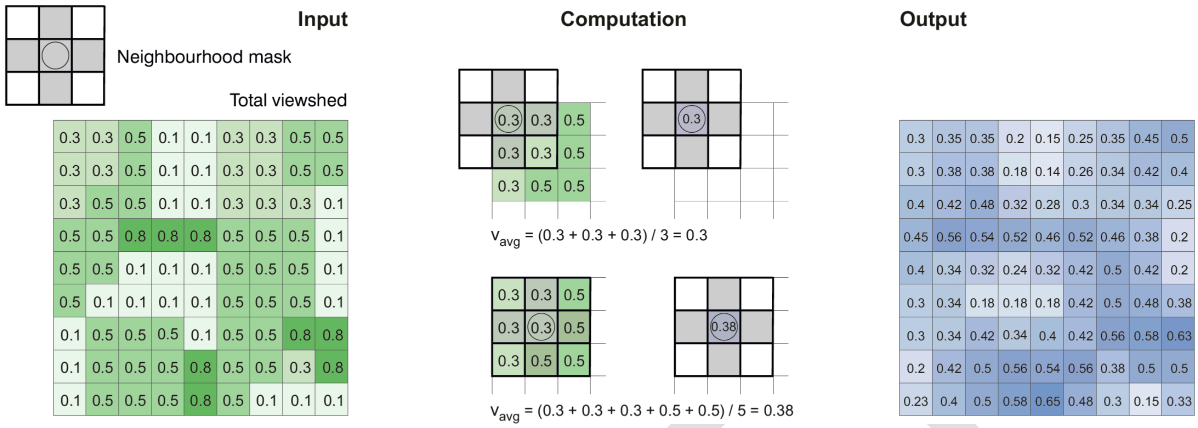

Fig. 4. Example of the VNC analysis process: a neighbourhood mask representing the VNC theory and a total viewshed are taken as input, in the computation phase the mask focuses on each cell of the total viewshed and writes the result of the evaluation method (in this case average visibility) to a new output raster file.

Visual prominence: the average visibility can be used to compute the visual prominence value as first proposed by Llobera (2003). The visual prominence V_{prom} of a focal location l_f is defined as the difference between the visual property value of the focal location and the average of the neighbourhood:

$$V_{prom}(l_f) = v(l_f) - V_{avg}(l_f)$$

Where $v(l_f) \in [0,1]$ is the normalized visual property value of focal location l_f. The visual prominence value indicates whether the focal location is much more visible than its surroundings (values close to 1), much less visible than its surroundings (values close to -1), or has a visual property value very similar to its surroundings (values close to 0).

Extreme values: rather than the overall values in a neighbourhood, one could also assume it is the minimum or maximum visual property value in the neighbourhood that is important. The minimum V_{min} and V_{max} maximum of a focal location are defined accordingly:

$$V_{min}(l_f) = \min_{l_i \in N_f} (v(l_i))$$

$$V_{max}(l_f) = \max_{l_i \in N_f} (v(l_i))$$

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Where $N_f = \{l_0, \ldots, l_n\}$ is the neighbourhood of focal location l_f and $v(l_i) \in [0,1]$ is the normalized visual property value of cell l_i. In addition, one can consider the range of visual property values present in a neighbourhood:

$$V_{range}(l_f) = V_{max}(l_f) - V_{min}(l_f)$$

A range close to 1 indicates a neighbourhood where both very high and very low visual property values are present. A range close to 0 indicates a neighbourhood with very little variation in visual property values, regardless of whether they are high or low.

Group-based analysis: the analyses above are based purely on the size and shape of the neighbourhood. If the VNC has a non-uniform structure, such as a subdivision in multiple distance bands or wedges, one can compare the values in each of the groups. These analyses do not return a visual property value, but indicate the group or groups containing the optimal value. The *VNC Analysis Tool* (Garderen 2017; see Section 3.4) offers the following group based analyses: G_{minavg} (returns the group with the lowest V_{avg}), G_{maxavg} (returns the group with the highest V_{avg}), G_{minval} (returns the group with the minimum value), G_{maxval} (returns the group with the maximum value), $G_{minrange}$ (returns the group with the lowest V_{range}), and $G_{maxrange}$ (returns the group with the highest V_{range}). If the same value occurs in multiple groups, the method returns an ordered string of all groups that contain this value.

Expectation-based analysis: when expectation values are specified for the different groups in the VNC, one can analyse how well the actual neighbourhood of a focal location matches the expected values. The *VNC Analysis Tool* offers two expectation-based methods: *Global RMSE* and *Grouped RMSE.* For both these methods, the output values indicate the difference between the expected values and the real visual property values in the neighbourhood. A high value (close to 1) indicates a large error, which means this location does not fit the assumption well. A low value (close to 0) indicates a good fit: the visual property values in the neighbourhood of this location are very similar to the expected values.

Global RMSE: the root-mean-square-error (RMSE) is a difference measure that can be used to compute the difference between the expected values of a VNC and the observed visual property values in the neighbourhood. For a given expected neighbourhood configuration N_{exp}, the resulting $RMSE_{global}$ of a focal location l_f is defined as follows:

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$$RMSE_{global}(l_f) = \sqrt{\sum_{l_i \in N_f} \frac{\left(v(l_i) - v_{exp}(l_i)\right)^2}{|N_f|}}$$

Where $v_{exp}(l_i)$ is the expected value of location l_i as expressed in N_{exp}. For each cell in the neighbourhood, the difference (or error) between the expected and real value is computed and squared, the mean of these squared errors is computed, and the square root of that is returned. Conceptually, computing $RMSE_{global}$ with a uniform expectation value of 0 or 1 is very similar to computing V_{avg}, as both can be used to evaluate whether the overall visibility in the neighbourhood is high or low. However, the RMSE is a more sophisticated measure with more nuanced results: many different configurations that have the same average will result in a different RMSE. On the other hand, V_{avg} has the benefit that the resulting values are simply an average of all visual property values in a neighbourhood, which makes the result easier to interpret.

Grouped RMSE: the RMSE-method described above weighs each location in the neighbourhood equally when computing the error. For assumptions which are related to VNCs with a structure in which the groups have different sizes, such as distance bands, this distorts the outcome: distance bands further from the focal location contain more locations, and would thus have a bigger impact on the result. The Grouped RMSE analysis counteracts this effect by computing the RMSE for each group separately and taking the average of the outcomes. For a partitioned neighbourhood $N_f = \{N_{f,1}, \dots, N_{f,k}\}$, the resulting $RMSE_{grouped}$ is defined as:

$$RMSE_{grouped}(l_f) = \frac{1}{k}\left(RMSE\left(l_f, N_{f,1}\right) + \dots + RMSE\left(l_f, N_{f,k}\right)\right)$$

Where $RMSE\left(l_f, N_{f,i}\right)$ is the RMSE for focal location l_f considering only locations in partition $N_{f,i}$ of the neighbourhood. Note that this method can be used for more than just distance bands: the neighbourhood can be partitioned into any kind of groups that should be weighted equally.

3.4. Implementation and Software

To facilitate the use of the VNC method in practice we introduce *VNC Analysis Tool*, an application that implements the creation of Visual Neighbourhood Configurations, assigning expectation values, and all evaluation methods as described above, through a user-friendly visual interface (Fig. 5). The VNC method was implemented in R, which provides both efficient computation methods and extensive options for the graphical display of data. Because

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R scripts can be tedious to work with for the average user, a graphical user interface was created using the R Shiny package for more convenient access to the settings and parameters. The tool can be downloaded from Github (Garderen 2017), and an extensive user manual written for an archaeological audience is available (Brughmans et al. 2017).

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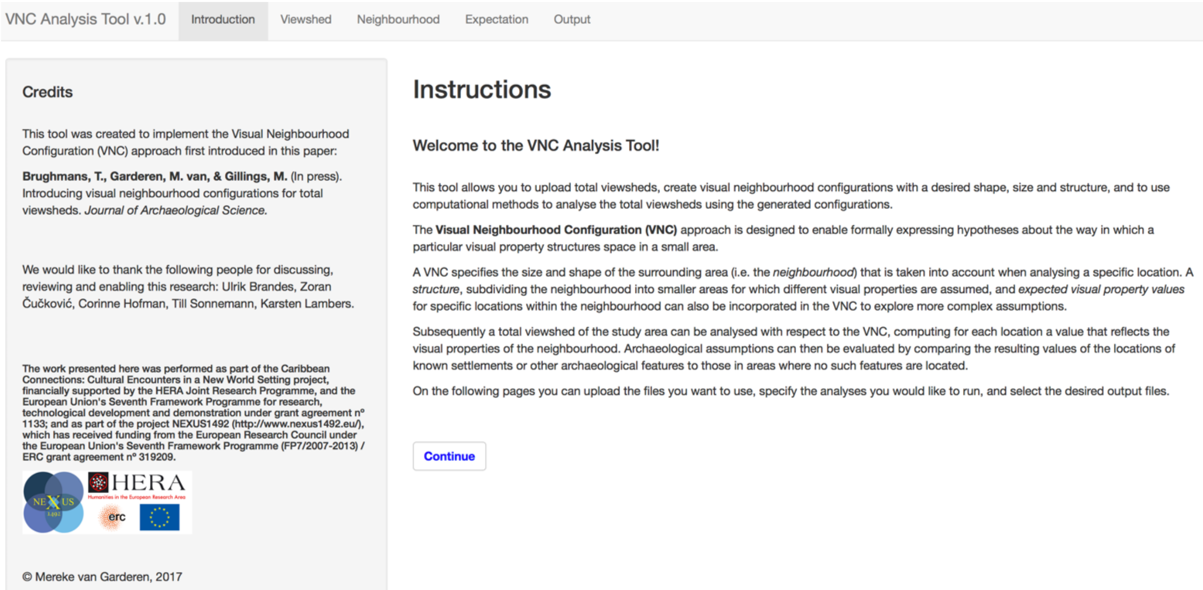

Fig. 5. Screenshot of the VNC Analysis Tool.

4. Case-study: The Exmoor Standing Stone settings

To assess the utility of the VNC approach, it will be used to revisit and extend analyses 1 and 5 of Gillings' (2015a) total viewshed study of the Exmoor standing stone settings. In addition, a third analysis was designed specifically to illustrate some of the unique functionality of VNCs and explore a previously unstudied aspect of the Exmoor standing stone settings. All experiments performed are listed in Table 1 (for a further VNC application, see Brughmans et al. 2017).

The focus of Gillings' (2015a) original study was a group of unusual prehistoric standing stone monuments that are characterised by the extremely small stones (up to 0.2-0.3m high) that were used to create them: Lanacombe I (L-I), Lanacombe II (L-II), Lanacombe III (L-III), Lanacombe IV (L-IV), and New Trout Hill (NTH) (Fig. 6). Described by Grinsell as 'unspectacular and difficult to find' (1970, 47), the fugitive nature of these structures has coloured interpretations of them, their hidden character being seen as both deliberate and meaningful (e.g. Tilley 2010; Gillings 2015b). The study sought to interrogate the specific interpretation that these monuments marked hunting locations, as well as explore more thoroughly the sense of concealment that accompanies them (Gillings 2015a). This was implemented through an analysis of their landscape positions using total viewsheds, in an attempt to determine whether the elusive character of these monuments was purely a consequence of the diminutive stones used to create them or whether it was reinforced by the careful and deliberate choice of hidden locales within which to erect them.

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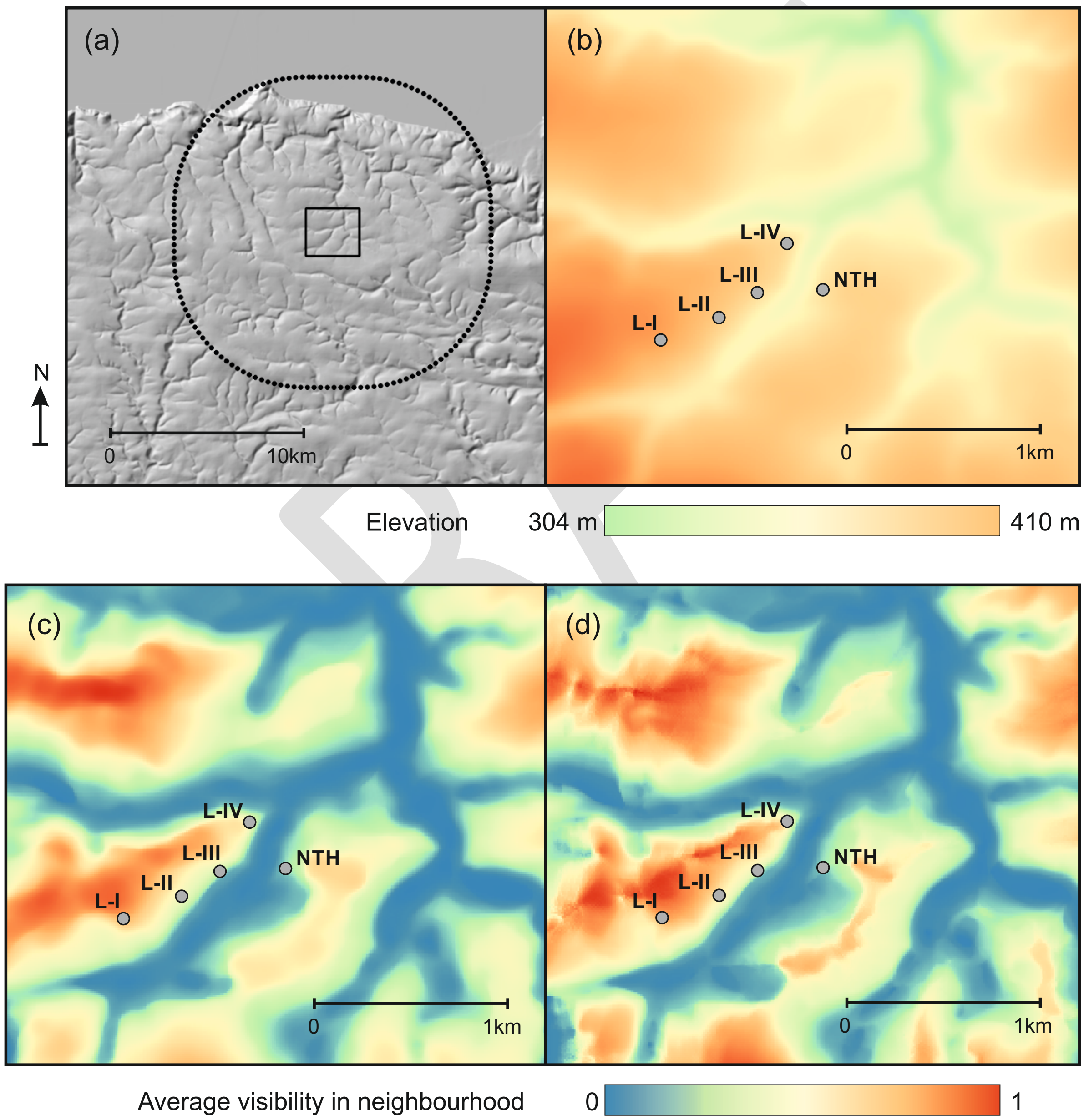

Fig. 6. (a) the black box indicates the core study area. In order to avoid edge effects, the area inside the dotted line was used as the input DEM for total viewshed creation (study area + 6880m buffer). (b) DEM of the study area and site locations. (c) views-from total viewshed showing a normalized version of how many cells can be seen from each cell in the study area. (d) views-to total viewshed showing a normalized version of from how many cells each cell in the study area can be seen.

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Table 1. Variable settings and input data for all experiments presented in this case study.

	Experiment	Spatial distribution	Neighbourhood shape	Neighbourhood size (radius)	Expectation	Input total viewshed	Method
Analysis 1	A1-20m-v_avg	Average low visibility	Circular	20m	na	views-to	v_avg
	A1-50m-v_avg	Average low visibility	Circular	50m	na	views-to	v_avg
	A1-150m-v_avg	Average low visibility	Circular	150m	na	views-to	v_avg
	A1-340m-v_avg	Average low visibility	Circular	340m	na	views-to	v_avg
Analysis 2	A2-20m-rmse_global	Low visibility surrounded by high visibility	Circular	Band1: 20m Band2: 130m	0 1	views-to views-from	rmse_global
	A2-20m-rmse_grouped	Difference error between band1 and band2	Circular	Band1: 20m Band2: 130m	0 1	views-to views-from	rmse_grouped
	A2-50m-rmse_global	Low visibility surrounded by high visibility	Circular	Band1: 50m Band2: 130m	0 1	views-to views-from	rmse_global
	A2-50m-rmse_grouped	Difference error between band1 and band2	Circular	Band1: 50m Band2: 130m	0 1	views-to views-from	rmse_grouped
Analysis 3	A3-8wedge-100m	Directional high visibility	45 degree wedge	100m	na	views-to	g_maxavg
	A3-8wedge-500m	Directional high visibility	45 degree wedge	500m	na	views-to	g_maxavg

4.1. Data

Stone setting positions were recorded in the field by Gillings using survey grade differential GPS. The total viewsheds used here as input data for the VNC approach (Fig. 6) were constructed on the basis of Ordnance Survey Landform Profile DTM data which has a 10m horizontal resolution, a vertical precision of 0.01m and a vertical accuracy of +/- 2.5m. It is interpolated from 5m interval contour data taken from 1:10,00 scale mapping (Ordnance Survey 2012). To provide a series of baselines for each of the analyses discussed below, Gillings' (2015a) original analyses were re-run on a smoothed version of this original DEM. The smoothing was intended to address a noted shortcoming of the original analysis by ameliorating the highly visible effects of contour artefacts in the source DEM used to generate the visibility products (see Reuter et al. 2009 for discussion of contour errors and Gillings 2015a, Figures 3, 7, 15-17 for examples of the impact these can have on total viewshed products). A smoothed version of the original DEM was created using focal statistics in ArcGIS 10.4.1 with a circular 5 cell window, replacing each focal cell elevation value with the mean of its surrounding neighbourhood. This threshold was selected in a pragmatic fashion after

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experiments with a range of smoothing windows, using a derived slope layer to visually judge when an appropriate balance had been reached between the removal of contour-artefacts and loss of critical topographic detail. Whilst we are aware that there is a compromise here, insofar as the inevitable reduction of maxima such as peaks and ridges by up to 3% will have impacted upon the viewshed determinations carried out (see Wheatley and Gillings 2000), this was deemed an acceptable trade-off given the extent of contour terracing and striping evident in the source DEM. A series of vector viewpoints were derived from the DEM, with a viewpoint placed at the centre of each of the 10m raster grid cells falling within the designated study area. To avoid edge effects, the extent of the DEM used in the visibility calculations was established by buffering the study area by the maximum viewing distance (6,880m). The total viewshed analyses were run in ArcGIS 10.1 SP1, using bespoke Python scripts on an Intel Core 2 Duo PC, 3.00Ghz, 4GB RAM, Win 7 (64 bit) SP1. The total viewshed analysis variable settings are given in table 2.

---INSERT TABLE 2 HERE---

Table 2. Total viewshed analysis variable settings. See Gillings 2015a for a discussion and justification of these settings.

Total Viewshed	Viewpoints	Target cells	Viewpoint offset	target cell offset	viewshed range
views-to	70,531	2,285,132	0	1.65	6,880m
views-from	70,531	2,285,132	1.65	0	6,880m

4.2. Analysis 1: hidden places?

The first analysis offers a different method for carrying out Gillings' Analysis 1 'hidden places?' which sought to identify those parts of the overall study area that offered the lowest chance of being seen (i.e. were least visible) (Gillings 2015a, 4). The original total viewshed analysis was carried out on a cell-by-cell basis, to generate a times-seen raster layer, i.e. each cell in the resultant views-to total viewshed encoded the number of other cells in the analysis region from which it could be seen (Fig. 6d). Once generated, this views-to total viewshed was visually evaluated in relation to the known locations of prehistoric settings by considering the upper- and lower-quartiles as the least and most hidden locations respectively.

To implement this and all other analyses below as a VNC requires: a) the establishment of a neighbourhood size and shape; b) a spatial distribution of visual property values; c) the selection of appropriate computational methods. Looking to the first of these factors, three values could be utilised in order to establish a meaningful neighbourhood size. In all cases a

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circular neighbourhood shape is adopted and the neighbourhood size is expressed as its radius. The first neighbourhood radius is based upon site extent (Table 3). The loose collections of standing stones that make up each of the discrete settings in the study area vary in maximum extent from 7.8 to 46.5m. This information was used to derive two neighbourhood radii; 20m and 50m respectively (the radii are rounded to the nearest 10m given the 10m resolution of our input total viewshed). The decision to exclude the smallest of the sites was a pragmatic one insofar as it fell beneath the raster resolution of the current study (10m) and therefore would be represented by a single cell. The second neighbourhood size is derived from the observed inter-site spacing in the study area (Table 4). These distances are nearest neighbour distances, so another way of describing this is as a minimum spanning tree for these 5 sites. If we take the mean of 306m we can halve this to obtain a radius, and round to the nearest 10m to give a workable neighbourhood radius of 150m. The final alternative based the neighbourhood instead upon Ogburn's limits of visual acuity multipliers (2006: Table 1). Here the maximum distance at which a 0.1m wide object (the typical width of the component standing stones) would be recognisable at the limit of normal 20/20 vision is 344m (rounded here to 340m). We can thus establish the radius of our neighbourhood as the maximum distance at which a standing stone would be recognisable as such. We assume a uniform distribution of visual property values and use the computational method V_{avg} to calculate for each cell in the total viewshed the average visibility within a circular neighbourhood around it. In so doing we aim to explore how hidden three types of areas are: the local area of a site, the area between sites, and the area within which standing stones are recognisable. Assuming that the hypothesis that the settings were deliberately intended to be concealed and hidden is correct, the expectation is that the standing stones would be located in areas that offer good hiding places; an extreme formulation of this hypothesis is therefore represented by a configuration where the visual property values are uniformly low.

---INSERT TABLE 3 HERE---

Table 3. Maximum site extents (m) of Exmoor standing stone collections.

Site	Maximum extent (m)
L-I	46.5
L-II	42.6
L-III	43.3
L-IV	7.8
NTH	19.9

---INSERT TABLE 4 HERE---

Table 4. Inter-site spacing (m) between nearest neighbours of Exmoor standing stone collections.

Sites	Distance (m)
L-I – L-II	325
L-II – L-III	245
L-III – L-IV	304
L-III – NTH	350

Results: As was the case for Gillings' original study, the results of analyses 1 and 2 will be interpreted by considering the lower quartile values (green) as locations with low visibility or locations that fit the hypothesis well when an expectation value is used, whereas the upper quartile values (red) are the opposite.

The original analysis 1 revealed that the standing stones were not located in the most hidden parts of the landscape; i.e. if the intention was to conceal them then there were far better locations in which to do so (Gillings 2015a, 4). The results of the new experiments largely confirm this conclusion (Fig. 7). L-I and L-II are located in very visible places at all neighbourhood sizes, whereas NTH is in a very hidden location when considering a 150m neighbourhood size and L-IV when considering a 340m neighbourhood size. These results suggest that only for the latter two sites we can support the hypothesis that their immediate surroundings afford a degree of concealment, though it is worth noting that the sites sit at the very edge of this zone. Moreover, for both LI and LII at all neighbourhood sizes the opposite hypothesis is supported: these sites are located in local areas that are highly visible.

---INSERT FIGURE 7 HERE---

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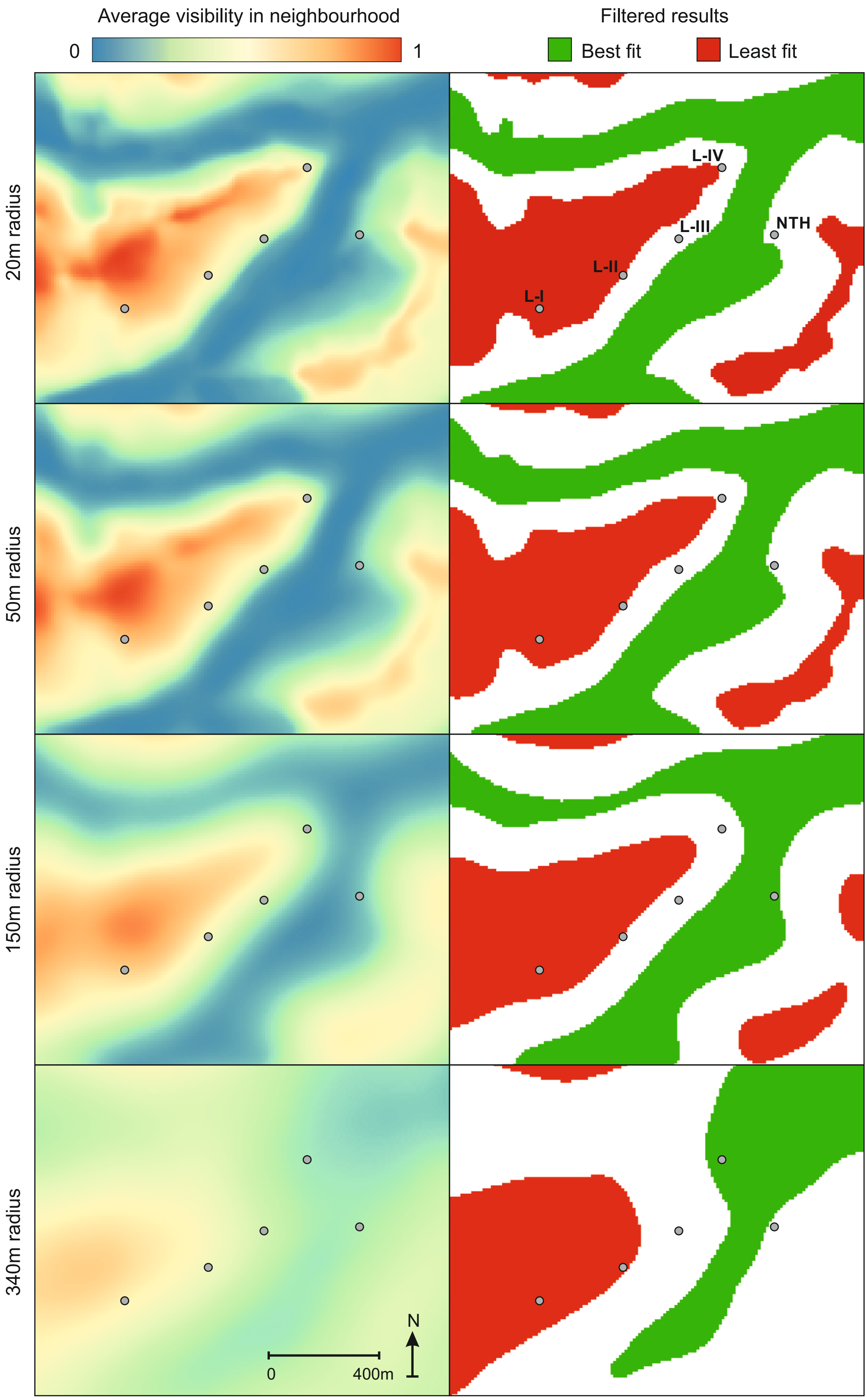

Average visibility in neighbourhood
0
1
Filtered results
Best fit
Least fit
20m radius
50m radius
150m radius
340m radius
L-IV
L-III
NTH
L-II
L-I
N
0
400m

462

Fig. 7. The rows show results of the four experiments performed in Analysis 1. The left column shows the precise results per cell ranging between 0 to 1 (i.e. low to high average visibility in neighbourhood). The right column shows the same results grouped in the lower quartile in green (locations offering the best fit with the hypothesis of low average visibility) and the upper quartile in red (worst fit).

4.3. Analysis 2: covert spaces

The second analysis revisits Gillings' (2015a, 5) Analysis 3 'Covert Spaces' which attempted to identify portions of the landscape that would have functioned well as places of surveillance or potential ambush – i.e. providing a concealed observer with expansive views. It did so by subtracting the normalised views-to from the normalised views-from total viewsheds.

For the revisiting of this analysis as a VNC, the obvious factor in determining neighbourhood size is visual acuity. A host of factors come into play here, from the visual acuity of deer themselves (the typical prey according to the hunting hypothesis) to the role of camouflage and deliberate concealment in making things (hunters for example) deliberately difficult to see. However, it is difficult to come to any convincing and persuasive (let alone definitive) values for variables such as this, especially given that hunters can camouflage and actively hide themselves more, or less, efficaciously, and the physiology of deer species suggests that their visual acuity is different in many respects from that of humans (e.g. D'Angelo et al. 2008). There is also the point that within any given population (of humans or animals) actual, as opposed to theoretical, acuity will vary widely.

A more straightforward approach is to move away from acuity altogether to consider instead site placement and extent as indicators of neighbourhood. We assume locations supporting hunting functions are characterised by being well hidden whilst being surrounded with good vantage points. This can be represented as a VNC by considering a circular neighbourhood around a focal cell, split into two distance bands: an immediate zone of hidden locations (i.e. low views-to), surrounded by a zone of good observation locations (i.e. high views-from). The radius of this circular neighbourhood is set at 150m – i.e. the halfway distance between consecutive stone settings (Table 4). The assumption here is that the settings were contemporaneous and that each setting marked an optimum hunting location that served to control a distinct chunk of the landscape through which game were expected to travel. If you moved beyond this distance you would effectively move to an adjacent setting location, so it offers a sensible neighbourhood size for the largest distance band. The smaller inner distance band represents the area covered by the stone setting itself, i.e. where a hunting party would be waiting. We use the maximum extent of the stone settings to define this inner neighbourhood (Table 3) and, as in analysis 1, use both a radius of 20m and of 50m. Using the $RMSE_{global}$

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and $RMSE_{grouped}$ methods, the low expectation value of the inner band will be compared with the views-to total viewshed and the high expectation value of the outer band will be compared with the views-from total viewshed.

Results: the original analysis suggested that only portions of the flat plateau tops, where none of the sites are located, can be considered covert spaces that could potentially accommodate hunting blinds (Gillings 2015a, 5). The new experiments not only confirm this conclusion but allow us to finesse and expand on it, because the two methods used reveal different aspects of the hypothesis (Fig. 8). The $RMSE_{global}$ method compares how well the total viewshed fits the expectation of the configuration by allowing each cell to contribute equally to the results, whereas the $RMSE_{grouped}$ method compares the fit of the two distance bands on equal terms regardless of the inequality in the number of cells in each band. The $RMSE_{global}$ method results indicate that L-I and to some extent L-II are located in covert spaces, because this method overemphasizes the importance of the larger number of cells in band 2 which show a good fit with the highly visible plateau tops close to L-I and L-II. Indeed, the results of the $RMSE_{global}$ method at both neighbourhood radii mirror closely those for the views-from total viewshed generated in the original programme of analysis and it is clear that the way in which the $RMSE_{global}$ parameter is calculated means that the results are effectively swamped by the visual prominence of the plateau tops. A much more nuanced result is gained from the $RMSE_{grouped}$ method which identifies a more fragmented picture with regard to possible covert spaces, that echoes closely the results of the original 'subtractive' analysis carried out by Gillings. This second analysis demonstrates that none of the sites are located in areas that match the stated hypothesis, with L-IV having a particularly bad fit.

---INSERT FIGURE 8 HERE---

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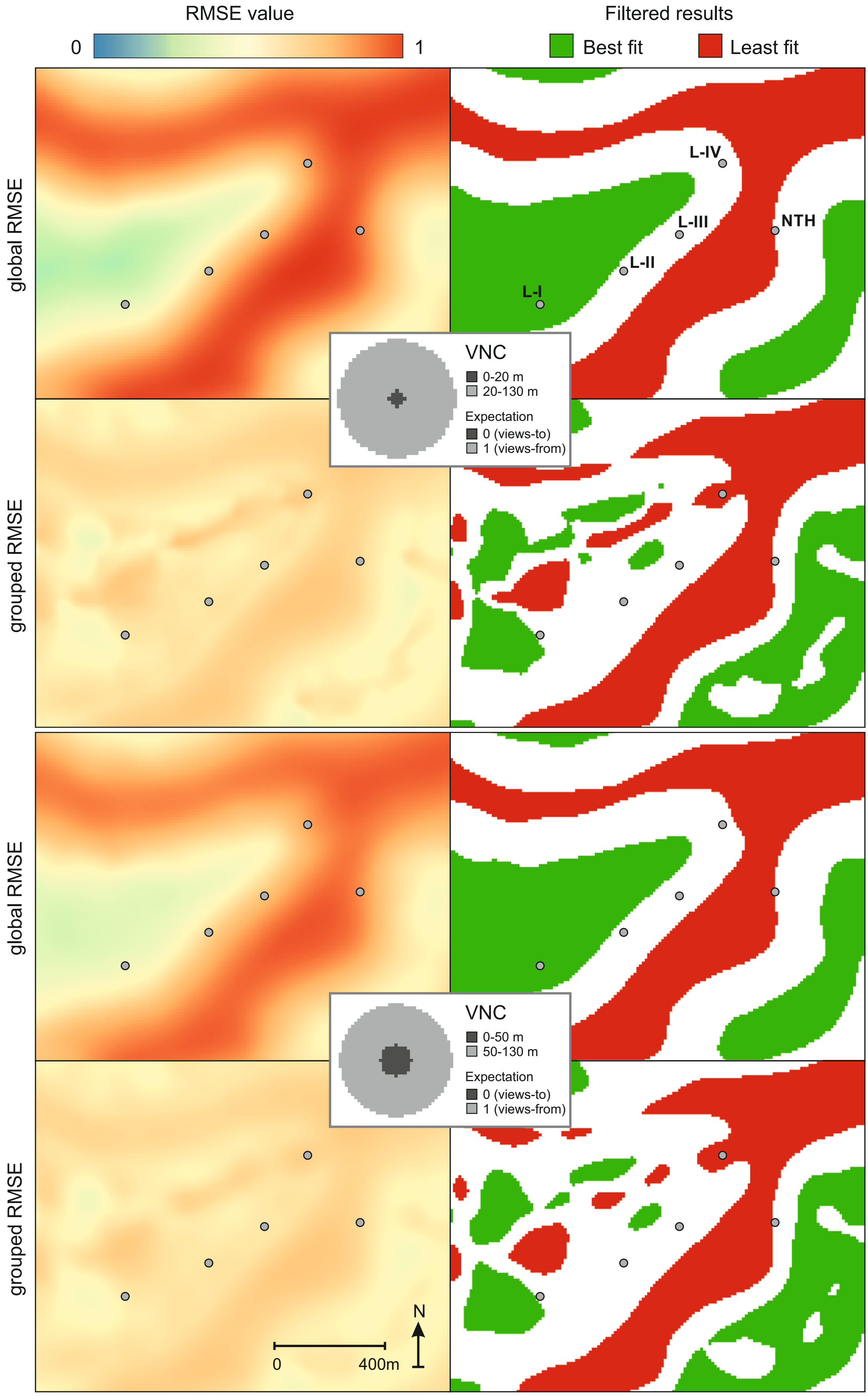
RMSE value
0
1
Filtered results
Best fit
Least fit
global RMSE
grouped RMSE
global RMSE
grouped RMSE
L-IV
L-III
NTH
L-II
L-I
VNC
0-20 m
20-130 m
Expectation
0 (views-to)
1 (views-from)
VNC
0-50 m
50-130 m
Expectation
0 (views-to)
1 (views-from)
N
0
400m

520

Fig. 8. The rows show results of the four experiments performed in Analysis 2. The top two rows use a VNC with an inner radius of 20m, and the bottom two rows an inner radius of 50m. The left column shows the precise results per cell ranging between 0 to 1 (i.e. low to high RMSE value). The right column shows the same results grouped in the lower quartile in green (best fit between expectation and total viewshed) and the upper quartile in red (worst fit).

4.4. Analysis 3: Direction, distance and orientation

So far the analysis has sought to demonstrate the utility of the VNC approach by showing how the method can be used to replicate the analyses carried out on a location-specific basis by Gillings. The final analysis seeks to illustrate how VNCs offer a clear and effective way to move beyond the original study by showing how the shape of the neighbourhood can be modified in order to better explore archaeological hypotheses. In the original study a neighbourhood (as opposed to cell-specific) mapping approach was adopted in order to begin to explore ideas of movement, distance and direction upon the visibility of one of the stone settings (Gillings 2015a, Analysis 5). Investigation of the hypothesis that the stone settings were meant to be seen (i.e. became most visible) only from certain directions and within certain distances should be ideally suited to the VNC approaches proposed here. In practice a series of 45 degree wedge-shaped configurations (implemented as a circle divided into 8 wedges) were used to determine for each location in the landscape the direction in which the set of locations with the highest average visibility is located, using the G_{maxavg} method. In the current study two radii were used for the wedge-shaped configurations, 100m and 500m respectively. The decision was largely pragmatic, designed to investigate local (100m) as well as more general (500m) scales of analysis. It was also limited by the size of the input total viewshed and the need to avoid edge effects. If there is a deliberate directionality to the siting of the monuments (i.e. they were intended to be approached and viewed in a certain way) we would expect locations within this preferred wedge (or wedges) in the direction of the sites to have highest average visibility. It is important to note that this VNC approach does not determine locations from which the sites can be well observed, but rather identifies whether there is a directionality in the sequence of high visibility locations and whether this points towards where the sites are actually found.

Results: considering a 100m or a 500m radius reveals very different results, emphasising directionality to high visibility areas close to sites respectively from the north and from the south (Fig. 9). The 100m radius enables us to explore the directionality of areas that can locally be considered to be highly visible. In this case all sites are more or less located in the direction of high visibility areas from locations to the north of the sites, except for L-IV. The analysis with a 500m radius is more dominated by the high visibility of the plateau tops than the local

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conditions surrounding the sites themselves, and does not reveal the sites to be positioned in the direction of the most highly visible areas. L-II, L-III and NTH are located in the direction of the highest visibility area from a few locations to their south, whereas L-I and L-IV from a few locations to the north. However, it is important to note that only in a few cases can we speak of sites being located in the direction of the most highly visible area from much of their immediate surroundings. For example, in the case of L-I in the 100m experiment we can argue that human movement over very short distances could have been structured by the site's location in the direction of the more visible area.

---INSERT FIGURE 9 HERE---

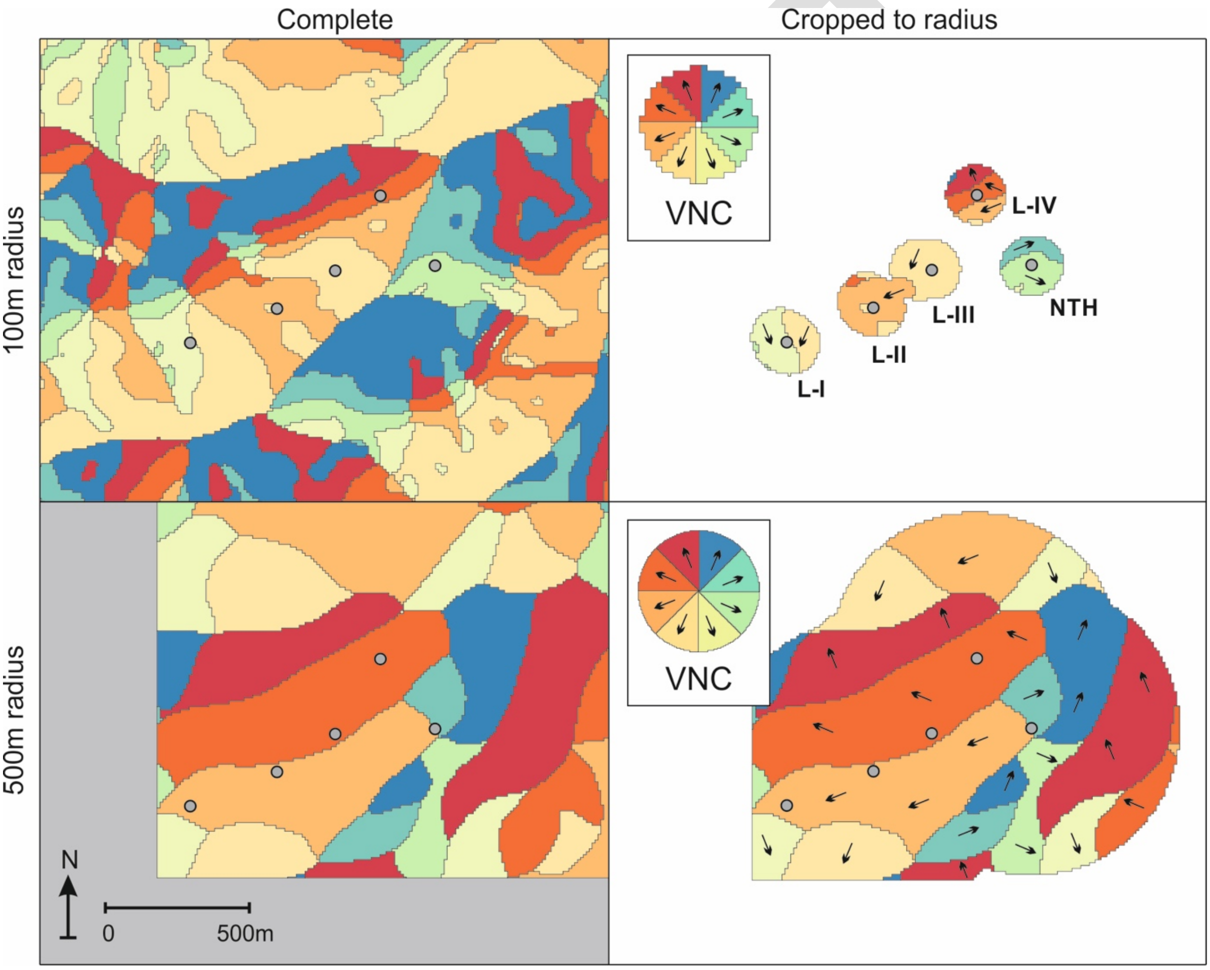

Fig. 9. The rows show results of the two experiments performed in Analysis 1. The left column shows the results for all cells. The right column shows the same results but only for those cells within a 100m (top row) or 500m radius (bottom row). The colours and arrows indicate per cell the direction in which the wedge with the highest average visibility is located. Notice how the top row shows the sites are located in the direction with highest visibility within 100m, whereas the bottom row shows the sites are not located in the direction with highest visibility within 500m.

4.5. Discussion

In the original study, a set of complex hypotheses about past human behaviour were operationalised through a process of simplification, with each cell in the source DEM treated as a discrete viewing/potentially viewed location that could be qualitatively evaluated through total viewsheds, or the simple mathematical manipulation of such. The VNC approach takes the total viewshed not as the end-point of the analytical programme but instead the starting point, providing a flexible set of tools that can be tailored to extract any number of derivatives, or parameters from a given total viewshed layer. The VNC analyses presented here have in large part added confidence to the conclusions drawn in the original study, confirming that the trends and properties identified for specific locations are echoed at wider neighbourhood scales. However, as well as repeating existing analyses the potential of the VNC approach to allow more sophisticated hypotheses about past visibility, of the kind familiar from more experiential approaches to landscape investigation, has also been demonstrated. Through careful manipulation of neighbourhood shape the question of preferential visibility has been addressed, identifying the possibility that the structures may have been erected upon sequential visual pathways that in turn may reflect natural patterns of movement through and across this landscape. Further it has shed important light upon the spatial scale at which these processes operated. This was revealed by the results of analysis 3. The 100m radius results (Fig. 9) indicate that the sites were located on visual pathways that either led upslope out of the valley bottoms (L-IV and NTH) or along the contour connecting sites (L-I, L-II and L-III) and from the valley top to the break of slope (L-I). This adds important weight to arguments that suggest that the structures were not related to hunting at all (and thus concerns with concealment and observation) but were instead key agents in the structuring of animal movement through this landscape (Gillings 2015b). That this pathway relationship manifested itself most clearly at the more local scale is clear from the results of the 500m radius analysis, which are dominated more by the high visibility of the plateau tops than the local conditions surrounding the sites themselves.

5. Conclusions

Visual neighbourhood configurations were presented as a new approach for exploring complex theories of visual phenomena in landscapes by processing total viewsheds. It recognizes that such theories most commonly concern the configuration of visual properties of areas around locations rather than solely the visual properties of the locations themselves, and that the typical

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approach to interpreting total viewshed results by classifying cell values is therefore problematic. It overcomes this issue by enabling one to formally describe aspects of the visibility theory: the shape and size of neighbourhoods as well as, where relevant, the structure and expectation of visual property values within the neighbourhood. A large number of analytical techniques has been presented to explore such theories and an open source software tool was developed to enable the implementation of the VNC approach through a user-friendly interface. The approach was illustrated through a case study on the Exmoor standing stone settings, exploring theories concerning their hidden nature and the marking of hunting locations. The case study results showed that the VNC approach can reproduce results obtained through alternative methods and that it can add unique new insights by significantly extending the range of formally explorable neighbourhood-based visibility theories. This work therefore presents a significant step forward towards richer and more complex theoretical formal visibility studies, contributing not only to the further development of the visualscapes concept (Llobera 2003) but also calls for a more radical 'unbinding' of GIS analyses from existing, and highly limiting, conceptual and methodological frameworks (Howey and Brouwer Berg 2017).

We believe the traditional reliance on binary viewsheds in landscape archaeology should be replaced by the more common use of total viewsheds and large-scale cumulative viewsheds: the technical limitations preventing their use at large spatial scales and with high resolution are virtually overcome; the uncertainty inherent in our data concerning settlement/feature distributions and past movements through the landscape makes the focus on known site point locations or small areas of landscapes undefendable; our theories concerning visual phenomena commonly concern areas and neighbourhoods rather than point locations. Such future studies should consider total viewsheds as a first step rather than the end point of a programme of analysis. A total viewshed offers a representation of a very particular structuring feature of an entire landscape, capturing a wealth of information that goes largely unused in current studies. To appropriately study our complex theories of how visibility phenomena structured past human behaviour we should draw on this wealth of information by manipulating and combining total viewsheds in a variety of ways through approaches like VNC. The full potential of the VNC approach will be revealed once total viewshed studies become more common and the VNC approach has contributed to a better understanding of a wider range of complex visual phenomena.

Acknowledgements

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