

Research article

A step towards advancing the mapping and spatial analysis of zoo-animal data; analysing the movement of multi-species zoological exhibits

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Abstract

Spatial data with explicit geographic coordinates has seen limited application in zoo biology, with collection and analysis methods developing more slowly than other methodologies. With the increasing availability of technologies that streamline these processes, spatial data can now be more efficiently integrated into standard zoo practices. This article presents a method for translating data from ZooMonitor into QGIS for spatial analysis. The approach was applied to data from four species housed in multi-species enclosures across two Irish zoological institutions. The resulting GIS-compatible data were used to explore the potential benefits of spatial analysis in enhancing captive animal welfare. Analyses included both traditional and novel (for ex-situ settings) spatial metrics: Modified Spread of Participation Index (mSPI), Minimum Bounding Convex Hulls, Mean Coordinates, Standard Distances, Standard Deviation Ellipses, and Kernel Density Estimators. While mSPI remains a valuable tool, its limitations when used in isolation are demonstrated. The advantages of combining multiple spatial measures are highlighted. Among the metrics examined, Standard Distance, Minimum Bounding Convex Hull, and mSPI were useful for understanding overall range. For finer-scale insights, Standard Deviation Ellipses and Kernel Density Estimators provided clearer interpretations of space use, better suited for informing husbandry and management decisions. Using multiple methods in tandem allows researchers to support more informed decisions regarding enclosure design and animal care. This study illustrates how spatial approaches, rarely applied in captive settings but increasingly feasible through tools like ZooMonitor, can offer new insights into animal welfare and management. The findings emphasize the importance of using a suite of spatial metrics rather than relying on a single method, which may introduce bias or limit interpretation. In conclusion, this article demonstrates the potential of GIS-based analyses to support zoological institutions in improving enclosure infrastructure and prioritizing animal welfare, particularly for critically endangered species.

Introduction

The need for applied conservation strategies continues to grow with the ongoing acceleration of global biodiversity loss (Brondízio et al. 2019). An accelerated rate of extinctions and species decline has been the driving force behind a revolution of research; examining the need for successful in-situ and ex-situ methods for stabilising and bolstering animal populations (Beer et al. 2023; Langhammer et al. 2024; Sutherland et al. 2023).

Key to the success of these projects is a deep understanding of the target species, their interactions and dependencies with the environment that they inhabit (Moloney et al. 2023). Many studies have focused on modelling and defining key characteristics of animals’ lives, such as behaviour, reproduction and movement (Kleinberger 2023; Mooney et al. 2023; Saito et al. 2024; Ward et al. 2024). The development of movement models has been an important focus of conservation science, particularly for in-situ settings, as these models can provide an

accurate understanding of population size estimates, population distributions, resource gathering behaviours, social dynamics and environmental dependencies (Hao et al. 2020; Milanesi et al. 2020; Miller et al. 2019, Miller et al. 2020). Conversely, to date, spatial data in the field of zoo biology have had limited applications for understanding the movement and enclosure usage of animals in captivity (Brereton 2020).

The majority of studies that use spatial data have been dependent on traditional pen-and-paper methods and incorporated into simplistic indices such as the modified Spread of Participation Index (mSPI) (Goswami et al. 2023; Hamilton et al. 2022; McConnell et al. 2022; Plowman 2003). These methods are used to gain insights into where animals spend their time and how they use their enclosures. The mSPI metric is used to determine how evenly an animal makes use of observer-designated zones in their enclosure, that are uneven in size and shape. The index accounts for this imbalance and produces a value from 0 to 1, the closer the value produced is to 0, the more evenly an animal or group makes use of the different zones in their enclosure (Plowman 2003).

Studies incorporating these indices have provided opportunities to update the care of species by improving enclosure design and husbandry practices, taking into account the behaviour of the animals and changing enclosure design based on the animals' needs (Hosey et al. 2023). For example, Goswami et al. (2023) used mSPI, alongside measures of welfare and behaviour, to examine the impact of different variables on a group of forty-one captive Asiatic lions *Panthera leo persica*. The results of the study showed that high-complexity enclosures with lower visitor presence resulted in animals displaying more positive welfare indicators than low-complexity enclosure with more visitors. Such analytical methods give weight to evidence-based husbandry and welfare, especially regarding enclosure design, complexity and the level of visitor presence (Collins et al. 2016; Hoy and Brereton 2022; Rose et al. 2021). This can be incorporated into design and refurbishment plans, to increase complexity of the enclosures and to better obscure visitors from the animals if necessary (Beer et al. 2023; Williams et al. 2021).

While mSPI has been central to developments in zoo research, it has limitations in showing finer details of enclosure usage when used alone. Although mSPI can give an initial understanding of space use, as a standalone it does not provide a complete picture for researchers to develop insights from. The index can tell the user if an animal is using different areas of their enclosure unevenly but cannot distinguish which areas are frequented more or less than others. The index also lacks the ability to provide insight into why animals are using different locations in their enclosure, nor is there any function to highlight specific enclosure features, such as feeding stations or shelter. The establishment of the zones is also a subjective process, with users defining the zones of interest based on their research question. Therefore, questions looking to examine how or why animals interact with specific features in the enclosure cannot be answered using mSPI alone. The methodologies explored in the current article provide additional tools, that when used alongside indicators such as mSPI, give a clearer understanding of animals' movements. Expanding beyond existing methods used in captive settings will allow researchers to fill the current research gap of zoo spatial analysis. By using multiple methods in tandem, researchers can advise more informed decisions for zoological institutions to effectively modify and build the infrastructure of their enclosures, while keeping the husbandry of the animals in their care as an utmost priority.

Understanding how animals move through their enclosure and why they choose what areas to use is becoming ever more critical to husbandry practices with the increasing prevalence of multi-species enclosures in zoos and aquariums (Chace and Margulis

2025; Green et al. 2022). Multi-species enclosures can provide an array of benefits to nonpredatory species, by allowing zoos to increase the overall size of enclosures and share it between multiple species (Bartlett et al. 2024). Having other species to interact with also provides a source of passive enrichment, giving the potential for animals to explore other social groups and dynamics unfamiliar to them (Daoudi et al. 2017; Wojciechowski 2004). A key goal for successful multi-species enclosures is to avoid mixing species that will interfere with or trigger aggression with the other animals in the enclosure (Law et al. 2021). By analysing spatial data, zoos would be able to assess what areas of an enclosure each species is using. Identifying potential conflict areas could lead to informed mitigation decisions, promoting positive welfare for all animals in the enclosure. Apart from assessing variables that cause conflict, spatial analysis could also be used to assess the willingness of animals to share space. For example, using home range analysis to examine potential overlap and commonalities in space use between individuals or groups could provide insights into social dynamics and inform husbandry decisions (Demšar et al. 2015). In this way, the potential benefits of passive enrichment in multi-species enclosures could begin to be quantified.

Zoo researchers have wide ranging foci in the types of research that they conduct, but in the case of fine-scale spatial data there is a significant gap in using this type of research for informing husbandry practices. Several reasons have contributed to this gap. For many proposed spatial analysis studies, automated, high-resolution recording of spatial data through Global Positioning Systems (GPS) technology, would likely be the preferred method for data collection. Limitations exist preventing this from always being the ideal option, such as cost of advanced technologies, accuracy and resolution of GPS units, ethical considerations and availability of small units for very small-bodied animals, such as many amphibians. It may also be the case that zoos wish to examine enclosures that are too small for current technology to provide accurate enough data points. Therefore, collecting this type of data by pen and paper methods may provide the most efficient and cost-effective option for zoos. Alternative methods do now exist, such as collection of spatial data on electronic devices, using software such as ZooMonitor (Wark et al. 2020). The uptake in data collection software has allowed for more centralised curating and management of data, however the advancement of spatial analysis continues to be slow due to issues of translating data between collection and analysis software. By overcoming the barrier of cross-software translation, it allows for methodologies to be parsed across fields of research and for new inter-disciplinary methods to be developed from the advances (Rose et al. 2019).

Some progress has been achieved in using GIS for the analysis of animals in the care of zoos and aquaria. For example, Stalter et al. (2024a) examined the home ranges and spatial preferences of a group of Nile crocodiles *Crocodylus niloticus* in captive settings, using a combination of kernel density estimators and electivity indices. Data in the study were collected on the ZooMonitor software but manually digitised and then analysed using ArcGIS Pro. A further study examined spatial preferences of captive Brazilian black-backed tarantula *Grammastola pulchra* to determine the potential preference for complex habitats over more simplistic options (Stalter et al. 2024b). That study actively shows how using spatial analysis in GIS software can be used to increase our understanding of captive animals' needs and enhance the quality of their care, especially for understudied species such as invertebrates. Metrione et al.'s (2024) study of sand tiger sharks *Carcharias taurus* translated data collected in ZooMonitor using a different technique to the method explained in the current article (see supplementary documentation). Their use of ArcGIS Pro, a subscription-based alternative to the QGIS software used in this article, for an aquatic species shows another multi-faceted

approach to examining spatial data. The study moves beyond examining data in two dimensions and fully incorporates three-dimensional assessment to truly represent the environment of aquatic species. Some previous studies have used the original Spread of Participation Index (Dickens 1955) to explore vertical space use of great apes (Ang et al. 2017; Ross et al. 2011). These studies provided very limited results when compared to the three-dimensional visualisations of sand tiger shark enclosure occupancy. The insights from the latter study can lead to greater understanding of the areas that this species use in their enclosure and help guide husbandry decisions.

With the advancement of technology in spatial data collection and analysis, the possibility exists to use more advanced digital tools to improve our understanding of how animals in captivity move through their environment (Congdon et al. 2022). The development of a new suite of tools is not required, as effective options already exist that are used most commonly for in-situ projects. Transferring analytical methods that have value to conservation projects in the wild into zoos and aquariums, and modifying their use to captive animal movements will expand the insights gained from spatial data (Rose 2022). For example, Peters et al. (2022) used a combination of GPS tracking and behaviour monitoring to analyse the patterns of African white-backed vultures *Gyps africanus* across Southern Tanzanian protected areas. The research examined the pattern of foraging and feeding behaviours connected to the animals and the time spent in certain locations around the protected areas to identify potential risk areas for poisoning attempts associated with human-wildlife conflict (Peters et al. 2022). These tools and methods have

been extensively used on wild populations, supporting various conservation goals and targets (Buchan et al. 2020; Creel et al. 2020; Ferreira et al. 2022; Goodall et al. 2019; Holloway 2020; Sergeyev et al. 2023); however, these methods are seldom applied to ex-situ populations, meaning further research is needed to identify how such approaches can inform husbandry practices.

With the mSPI, arguably the most used measure of space use analysis to date in zoo research, we used this as a yardstick to compare commonly applied in-situ methods to spatial data collected in captive settings. With only a handful of available examples of spatial analyses being used for insights for captive animals, this research should provide a critical insight into the benefits of GIS-informed spatial analysis. We hypothesize that by comparing the output of the mSPI to the other chosen metrics, this will highlight the limitations of the mSPI and provide a starting point for comparing the benefits and drawbacks of different methods to use in captive settings. To achieve this, we analysed spatial data collected across two Irish zoological institutions. We aimed to collect fine-scale spatial data using tools easily accessible to zoo researchers (i.e. ZooMonitor) and convert these data into a more quantifiable and useful format in GIS software. After devising a method for translating the data across software, the aims were to examine how currently available spatial analysis tools in GIS software could add insight alongside a common zoo research method (i.e. mSPI) to provide more robust and informative insights into movement habits of the focal animals. This article is an initial probe into examining the benefits of these potential insights to the welfare of captive species and the husbandry and management decisions of those tasked with caring for them.

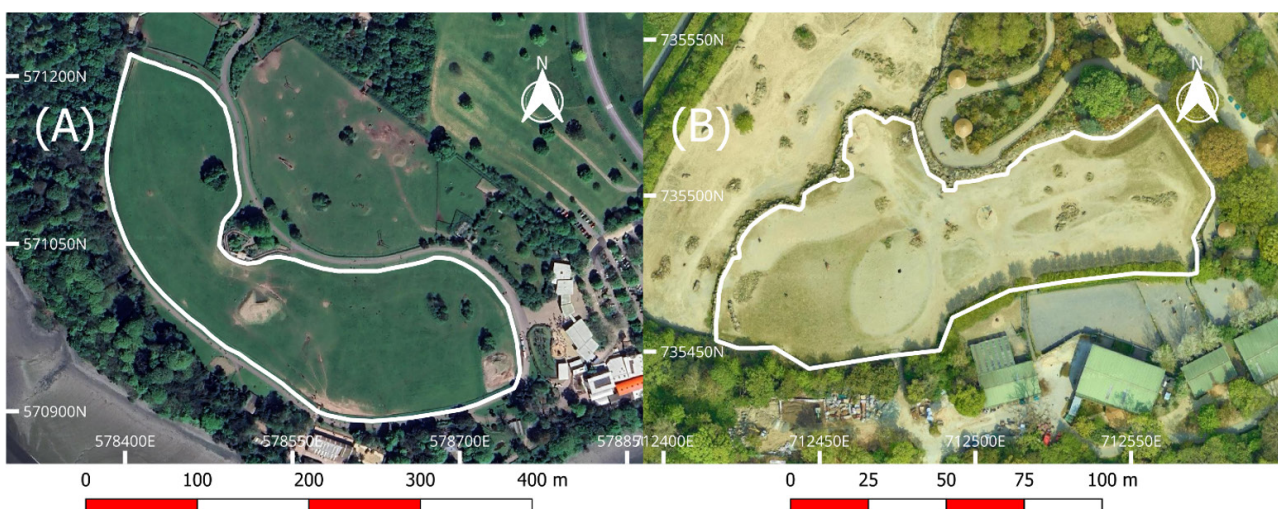


Figure 1. Satellite view of the enclosures examined. (A) displays the Fota Wildlife Park enclosure with the boundary highlighted in a white line. (B) shows the Dublin Zoo enclosure with the same. The figure also shows orientation, scale and coordinates of the enclosures respectively.

Methods

Study Sites and Focal Species

Data for this project were collected at Fota Wildlife Park, Carrigrohilly, Co. Cork, Ireland and Dublin Zoo, Phoenix Park, Dublin, Ireland (Figure 1). Two different enclosure types exist, providing the opportunity to test the methods in two locations with similar species composition. Fota Wildlife Park's enclosure is a naturalistic grass paddock covering an area of approximately 51,000 m² with some foliage and trees in small, fenced off areas within the paddock. In comparison, Dublin Zoo's enclosure covers an area of approximately 7,700 m² and has a different substrate composition comprised mostly of sand and/or gravel with small areas of grass. All foliage is found around the boundary of the enclosure, outside the boundary fence but still within reach of the animals.

Data were collected between the months of September 2023 and August 2024 in Fota Wildlife Park and the month of June 2023 for Dublin Zoo. The paddocks at Fota Wildlife and Dublin Zoo have similar species compositions and consist of three common species. These are zebra *Equus quagga* (Fota n=5, Dublin n=6), giraffe *Giraffa camelopardis* (n=10, n=9), scimitar-horned oryx *Oryx dammah* (n=7, n=10). One species, ostrich *Struthio camelus* (n=4), is only located in Fota Wildlife Park.

Data Collection

ZooMonitor is a programme specifically designed for the purpose of collecting and analysing behavioural, spatial and welfare data on captive species (Wark et al. 2019). Data were collected using the ZooMonitor software in sample periods of two hours, with the behaviour and location of every animal recorded every three minutes using the scan sample technique designed for behavioural data collection (Altmann 1974; Moloney et al. 2023), although in this article only the location data are used. When collecting data, enclosures were scanned from left to right, noting the locations and behaviours for every animal visible in that scan. Data were then uploaded to the ZooMonitor server where they are stored and can be downloaded as a Microsoft Excel (.xlsx) file. Data were recorded for this study without identifying and distinguishing individual animals as the identities of all animals could not be reliably ascertained for each data point.

Users can upload an enclosure image to ZooMonitor for the purposes of spatial data collection. This image is taken by the software and placed on a grid of pixels that is 600x600 in size. Each pixel is used as a reference point. When collecting data points and entering the location of an animal, the location is designated an XY coordinate based on the pixel highlighted on the grid. This custom XY coordinate is the focus of translation for the purposes of uploading these data to GIS software.

Process of Translation

ZooMonitor data is primarily used to visually describe patterns and is not easily transferred into existing GIS software. The process of translating ZooMonitor data into QGIS was achieved by creating a point grid shapefile containing the same number of points as the number of pixels covered by the image used for data collection in ZooMonitor. This image was then georeferenced and orientated to ensure accurate geolocation. This method can be replicated to any coordinate system (e.g., Latitude/Longitude, Universal Transverse Mercator). Subsequently, this creates a digital version of the spatial data collected via ZooMonitor to be plotted in any GIS software. A full step-by-step guide to the conversion process has been included in appendix two.

Measuring Space Use

Space use was examined using a combination of methods

traditionally used separately for in-situ and ex-situ settings. The most predominant ex-situ method of mSPI (Brereton and Fernandez 2022) was used, while five in-situ methods were chosen to compare against the output of the mSPI. Beyond this, a novel analytical measurement was examined for each of the in-situ methods consisting of a habitat utilisation percentage of the outputs, expressing the dimensions of the space primarily used by each species.

Modified Spread of Participation Index (mSPI)

The mSPI is a tool used widely by zoo biologists to assess the spread of spatial data across an enclosure and understand how evenly an animal or group of animals use the different zones. To establish the zones to be examined, the enclosure can be divided up based on features of the enclosure that stand out. This index accounts for the chosen zones to be of different sizes and shapes, improving on the previous version of the index which required zones to be uniform (Plowman 2003). This may be the feeding stations, visitor locations or shelters. The index is calculated by dividing the enclosures into zones and using the formula:

$$mSPI = (\sum |f_o - f_e|) / 2(N - f_{emin})$$

where the sum of all absolute values of the expected frequency (f_e) is subtracted from the observed frequency (f_o) of animals in each zone individually. This is divided by two times the total number of observations (N) minus the smallest expected frequency value (f_{emin}). The expected frequency is calculated from the assumption that the total number of data points are spread completely evenly across the full enclosure. Using a ratio of the areas of each zone will provide the expected frequency of each.

The result of the index will be a value ranging between zero and one, the closer the value is to zero, the more evenly the animal or group being examined use their enclosure. mSPI has been used extensively as one of the predominant methods of examining zoo animal enclosure usage (Goswami et al. 2023; Rose et al. 2022; Saito et al. 2024).

Mean Coordinate (MC)

The Mean Coordinate is a tool that calculates the mean longitude and latitude (or x and y coordinate) of a sample of points and displays this location as a single data point. The mean coordinates of the collected data were included in the results as they are a component of the calculation for both Standard Distance and Standard Deviation Ellipse. Mean coordinates are predominantly used in space use studies to identify locations that are considered anomalous, particularly with regard to expected space use and travel time between locations (Rodriguez Recio et al. 2013). Therefore, while they are not seldom used on their own to quantify space use, they provide a robust quantification of expected or normal space use.

Standard Distance (SD)

Standard Distance is calculated from the first standard deviation and mean coordinate of the data used in the analysis. For the purposes of this metric, the first standard deviation is taken as approximately 68% of data points found closest to the calculated mean coordinate. Therefore, the standard distance calculates the mean distance covered by the first standard deviation displayed as a radius around the mean coordinate.

Standard Deviation Ellipse (SDE)

The Standard Deviation Ellipse tool is similar to the Standard Distance, as it calculates the result from the first standard deviation of the selected data. This tool produces an ellipse indicating the mean distance covered in the first standard deviation but also

Table 1. Modified spread of participation index values calculated for both Fota Wildlife Park and Dublin Zoo. Values were calculated for each species individually and for the collected data in total. Values range between zero and one. As values approach closer to zero, this indicates an animal/group using their enclosure more equally.

Fota Wildlife Park		Dublin Zoo	
Total	0.213	Total	0.258
Giraffe	0.413	Giraffe	0.507
Zebra	0.391	Zebra	0.405
Oryx	0.267	Oryx	0.315
Ostrich	0.648	N/A	N/A

gives an indication of directionality based on the orientation of the produced ellipsoid polygon. This provides an understanding of the directionality of animal movements as well as their core usage areas.

The MC, SD and SDE have been used in a wide range of ecological assessments for wild species. Rogers et al. (2025) present clear arguments in their article for the benefits of using these tools to assess the health and distributions of bee populations in-situ and argue the tools should be adopted more by ecologists studying their focal species of honeybees to expand their understanding of these species' space use.

Minimum Bounding Convex Hull (CH)

Convex hulls are a bounding geometry that show the spatial limits of a point-based dataset in a polygon formed of the outermost points of location data. Essentially, this tool shows the full area covered by the data.

The CH tool is used by ecologists to aid in establishing the home/core ranges of focal species. Yeum et al. (2024) used CH alongside other tools to explore the differences in habitat use and core ranges for common kestrels *Falco tinnunculus* across several months focusing on their adaptation to the use of urban environments.

Kernel Density Estimator (KDE)

Kernel Density Estimators are a tool used to understand the density of point data representing the presence of species in an area displayed in heatmaps. The tool calculates density by counting the number of recorded occurrences in a user-defined radius around each data point and creating a visual representation using a colour spectrum representing density. The radius in this instance set to five metres. This tool is similar to ZooMonitor's built in function of producing heatmaps; however, it overcomes several of the limitations ZooMonitor has. By using the KDE in a software designed for GIS analysis, all data can be examined in an appropriate orientation and scale, depending on the users' requirements. In ZooMonitor, the heatmaps produced have no scale or, orientation and produce the "hotspots" based on an undefined unit. Users can change this unit but have no scale or understanding of how this may relate to the body size of animals or the enclosure size itself. In GIS software this radius that is used for producing heatmap can be set to a specific unit and size based on the needs of the user, as previously discussed.

In-situ projects have successfully used KDEs to assess home ranges and priority areas for species both terrestrial and marine

(Desbiez et al. 2020; Liu et al. 2020; Tezel et al. 2020). These projects have used the methodology to understand the spatial priorities for different species and provide recommendations based on evidence for key conservation strategies that could be deployed. Beyond broad conservation goals, KDEs have also been used to address specific threats to species. Overall, KDEs have been used successfully in-situ for both general and specific research topics and to expand general knowledge of species and answer direct, focused questions. Taking these tools into ex-situ settings will allow similar tactics to be deployed on spatial data for animals in captive settings.

Habitat Utilisation Percentage (HUP)

To examine the data across some of the various methods used (CH, SD and SDE), a novel metric was explored. The HUP of each output was calculated and compared across the different enclosures and species. To calculate the HUP, the outputs of each space use technique were limited to the boundary of the enclosure, excluding any of the output which extended beyond the enclosure of interest. The remaining area was measured and divided by the total area of the enclosure producing a percentage of the enclosure covered by that specific metric.

Ethical Approvals

This research was carried out with approval and oversight of both Fota Wildlife Park's Ethics Committee and University College Cork's Animal Experimentation Ethics Committee under project reference #2021/031.

Results

Modified Spread of Participation Index (mSPI)

The results of the mSPI show similar patterns across both enclosures (Table 1). Across both enclosures, the values range between 0.267 and 0.648 for the individual species indicating space use ranges from somewhat even to a middling degree of evenness of space use. When examining the enclosures in total, Fota Wildlife Park and Dublin Zoo had mSPI values of 0.213 and 0.258 respectively. Across the two different enclosures, the species have values that are all within a difference of 0.1, indicating similar patterns of space use.

Habitat Utilisation Percentage

Table 2 displays the HUP of the three space use methods after restricting the output to within the boundary of the enclosure.

Table 2. Habitat Utilisation Percentage of output for each method displayed as a percentage. Percentages are calculated by cutting the output of the methods to the boundary of the relevant enclosure and comparing the resulting areas to the area of the total enclosure. Results are displayed across the two different enclosure locations.

Habitat Utilisation Percentages		
	Fota Wildlife Park	Dublin Zoo
Minimum Bounding Convex Hull		
Giraffe	72%	82%
Zebra	59%	52%
Oryx	71%	83%
Ostrich	85%	N/A
Standard Distance		
Giraffe	44%	28%
Zebra	24%	23%
Oryx	23%	43%
Ostrich	51%	N/A
Standard Deviational Ellipse		
Giraffe	21%	14%
Zebra	17%	8%
Oryx	21%	15%
Ostrich	13%	N/A

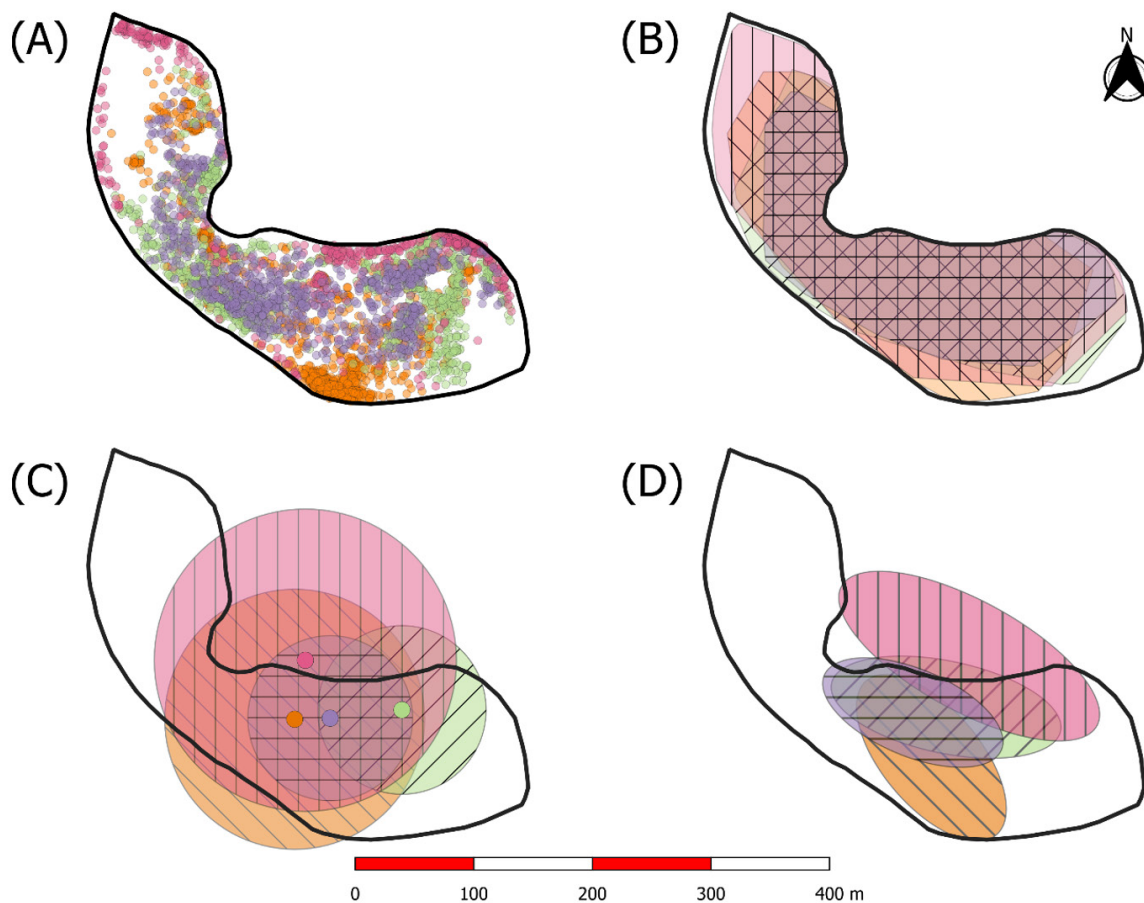


Figure 2. The methods used for assessing spatial data using QGIS for Fota Wildlife Park. Results are colour coordinated with each species displayed as a different colour. Giraffe=Orange. Oryx=Green. Zebra=Purple. Ostrich=Pink. (A) displays the total collected data split by species. (B) displays the convex hulls (CH) generated from the data after being clipped to the extent of the enclosure boundary (C) displays the results of the standard distance and mean coordinate tools, with the colour of the centroid matching that of the standard distance (SD) and (D) displays the results of the standard deviation ellipse (SDE) results calculated using the same mean coordinate in (C). Figure includes north arrow and scale bar.

The results are displayed as a percentage. The values of the HUP decrease across the different tools (CH>SD>SDE). This is expected as each tool in turn uses a more refined subset of the data.

GIS Metrics

Figures 2 and 3 display the visual output of the GIS metrics explored for Fota Wildlife Park and Dublin Zoo respectively. Figure (A) shows the raw data with each species displayed in a different colour. Figure (B) represents the minimum bounding convex hull of each species when it is restricted to the boundary of the enclosure. Figure (C) represents the standard distance and mean coordinate, used for calculating the standard distance. Figure (D) represents the standard deviational ellipse. Results of the convex hull indicate that the animals generally make use of a large majority of their enclosure, which is supported when examining Figures 2(B) and 3(B).

Subplots were used to show the raw spatial data (Figures 2A and 3A), convex hulls (Figures 2B and 3B), Standard Distances with Mean Coordinate (Figures 2C and 3C) and the Standard Deviation Ellipses (Figures 2D and 3D).

Kernel Density Estimator (KDE)

Figure 4 displays the KDE results for both Fota Wildlife Park and Dublin Zoo, faceted by species and comparing across the two enclosures. The KDEs display the presence or absence of data points around the enclosure but also indicate the relative density of data points with colour. The presence of grey or colour indicates the presence of the animals in the enclosure, however the more intense the colour, the more densely aggregated the data points are.

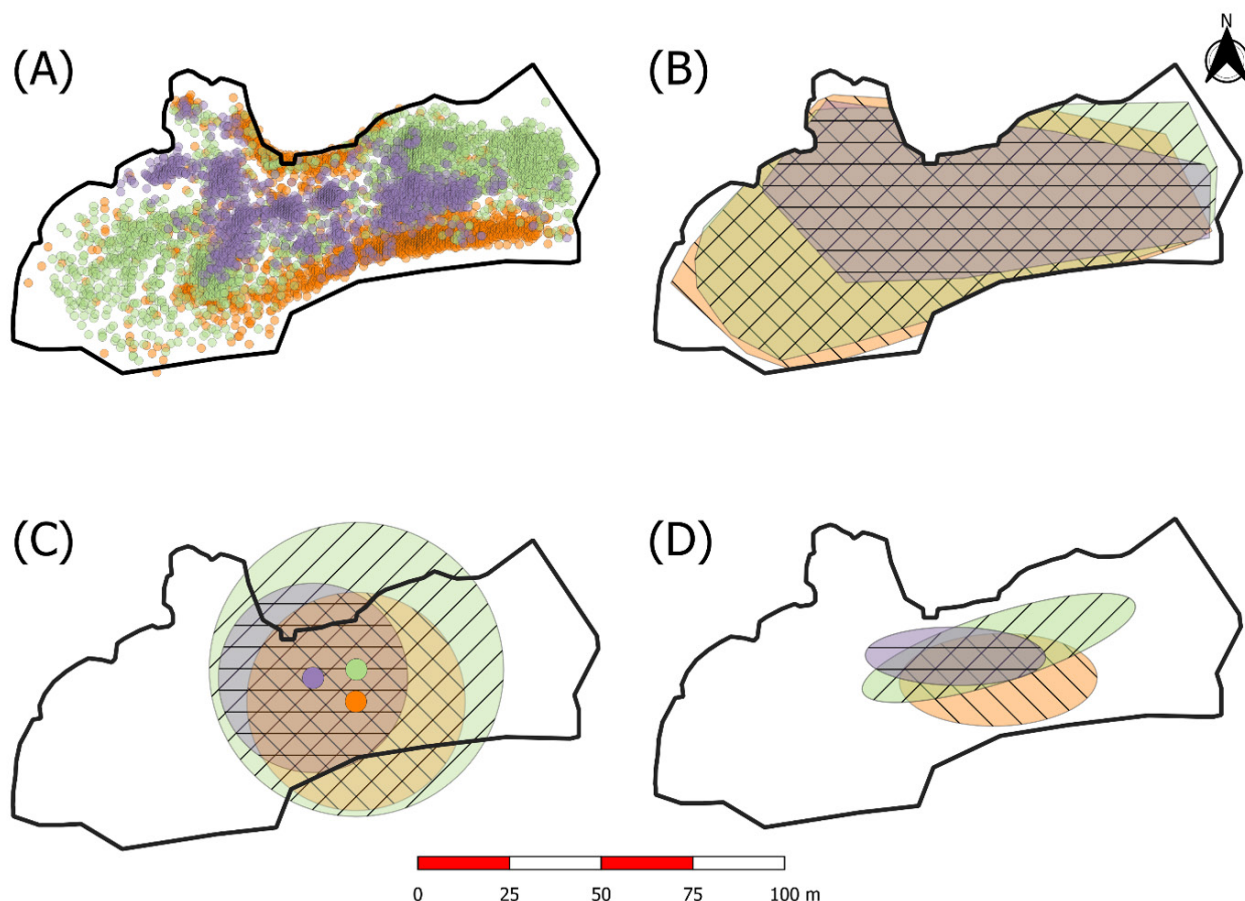


Figure 3. The methods used for assessing spatial data using QGIS for Dublin Zoo. Results are colour coordinated with each species displayed as a different colour. Giraffe=Orange. Oryx=Green. Zebra=Purple. (A) displays the total collected data split by species. (B) displays the convex hulls (CH) generated from the data after being clipped to the extent of the enclosure boundary (C) displays the results of the standard distance and mean coordinate tools, with the colour of the centroid matching that of the standard distance (SD) and (D) displays the results of the standard deviational ellipse (SDE) results calculated using the same mean coordinate in (C). Figure includes north arrow and scale bar.

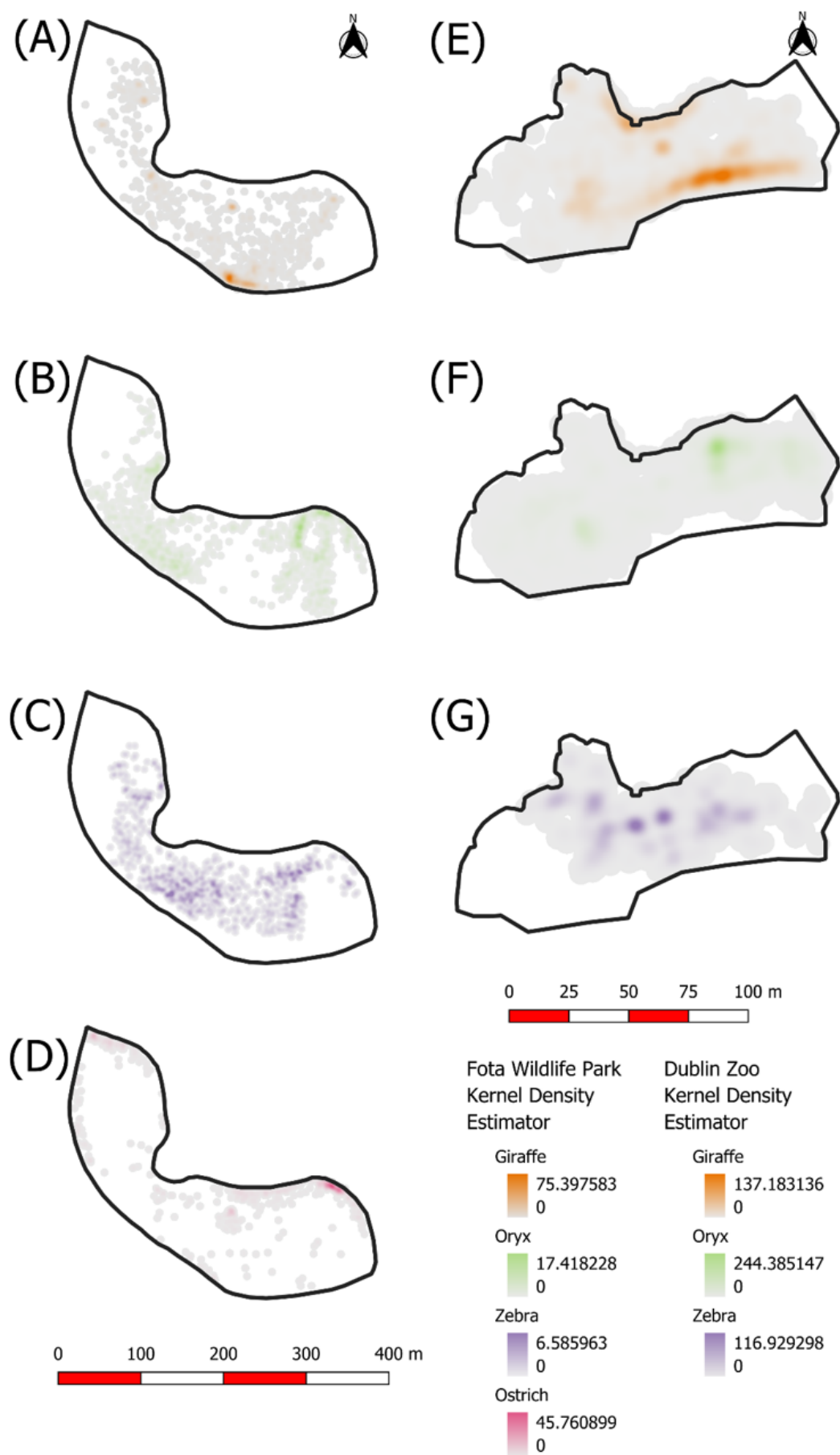


Figure 4. Kernel density estimator output for both Fota Wildlife Park (A–D) and Dublin Zoo (E–G). Results give indication of density where the more colour visible, the denser the congregation of data points. Images are colour coordinated by species. Giraffe=Orange. Oryx=Green. Zebra=Purple. Ostrich=Pink. Figure contains orientation north arrow and respective scale bars. The legend included in the figure displays the range of each KDE from minimum to maximum density within the selected radius for generating the KDE, in this case five metres.

Discussion

The main aim of this research was to examine the potential application of GIS spatial analytics commonly used in in-situ settings for animals kept in zoos and wildlife parks. A variety of methods were examined and found to produce varying results depending on the type of tests being employed (Figures 2–4, Tables 1–2). The chosen measures of space use provide different insights into the animals being examined depending on the metric. When examining a single metric on its own, this provides only a piece of the overall puzzle. From the results obtained, each of these metrics provide some insight when used alone, but the individual insights can give different impressions of animals' space use. To achieve the best overall understanding of the data collected, multiple metrics should be used in tandem to better understand the space use of the focal species. Taking this approach will better inform any decisions being made to change enclosure design or husbandry practices to influence the welfare of the animals being examined.

Examining the dynamics of movement within this multi-species enclosure can aid in improving the existing knowledge base of how multi-species enclosures may benefit or hinder the quality of life experienced by these animals. To date, some multi-species assessments have included a degree of spatial analysis (Daoudi et al. 2017; Leonardi et al. 2010) but few have pushed beyond the recognised ex-situ methods such as the mSPI. From the results of this study, a determination can be made that using a single tool that aggregates spatial data, such as the mSPI does not provide adequate information to fully understand enclosure space use. The mSPI values for the three ungulate species fall between 0 and 0.5, which fall between the midpoint of the mSPI scale and 0, indicating perfectly even space use (Table 1). These results may lead observers to believe that most or all areas of the enclosure hold equal significance to the animals. While the Convex Hull (CH) outputs concurred with the results of the mSPI, in as far as showing the animals are seen to be present in all areas of the enclosure, the Standard Distance (SD) and Standard Deviation Ellipse (SDE) tools provided conflicting results (Figures 2–3, Table 2). This is because the SD and SDE tools only analyse the first standard distribution of the data (approximately the 68% of data around the mean), therefore removing the outliers and less frequented zones of the enclosure. Therefore, when using the SD and SDE, observers are given a clearer view of where animals are spending most of their time. For the ungulates in this study, the SD and SDE show that most data points are within <30% of the total area of the enclosure (Table 2), contradicting the mSPI. The only exception to this are the giraffes in Fota which have a SD covering 44% of their enclosure.

To explain the conflict between the methods, looking to their use for in-situ projects can help to understand the difference. For spatial ecologists examining the ranges of animals in the wild, it is not always necessary to include all records of observed animals. The home range is generally seen to be the overall coverage of an area that an individual or population of a species covers in their day-to-day activities including socialising, foraging, and hunting. To understand the space use of these behaviours, tools have been developed with the capacity to focus on a specific subset of data that excludes outlying data points that may introduce bias (Boyle 2021; Mukomberanwa et al. 2024). In this study, the settings for the CH used the full dataset while the SD and SDE use only the first standard deviation. In the context of zoos and wildlife parks, restricting the data being analysed by these tools makes sense for studies that are focusing on decisions to edit or modify the enclosures of these animals to ensure that outlying data points do not influence decisions. For tools such as the mSPI or CH, using the full dataset introduces a potential bias in the interpretation

of animals' movement and space use, which could lead to less efficient decision making.

When using these metrics to plan for changes in husbandry routines, enclosure designs or other amendments, it is crucial to plan accordingly for the type of question being asked (Brereton 2020). If a question needs to explore whether animals are using the full extent of their enclosure, the mSPI and CH output could be sufficient in answering these types of queries. Figures such as 2(A) and 3(A) which display the raw data of species presence can support these assertions in a broad sense. If a more in-depth question is being explored, such as where to place new feeders and/or environmental enrichment, then a narrower view may be required such as created by SD or SDE (Desbiez et al. 2020; Liu et al. 2020; Yeum et al. 2024). These tools may also provide insight into potential conflict zones in the overlap areas most frequently used by all in multi-species enclosures. The more specific location data from SD and SDE outputs provide the key insight that the mSPI and CH lack, namely what specific areas are being used the most by the animals in question. Thereby showing that the more tools used with the dataset, the greater understanding obtained about the spatial habits of these animals (Rodríguez Recio et al. 2013; Rogers et al. 2025; Tezel et al. 2020).

Another observation from these methods were the fact that the SD and SDEs often fell outside the boundary of the enclosures (Figures 2 and 3). While this raises questions about their applicability in captive settings, due to the restrained nature of enclosure and the inability of animals to go beyond the enclosure boundaries, it does not remove all legitimacy of using these types of methods. In this study, the most extreme examples would be Figures 2(C) and 2(D) where the visualisations of both SDs and SDEs expand beyond the enclosure boundary in almost all cases. This is explained by the shape and orientation of the Fota Wildlife Park enclosure having a kidney-like shape with the north-west section of the paddock occupying more northern coordinates than a significant portion of the enclosure. This results in the mean coordinate of the datasets being offset north and displacing both the SDs and SDEs that rely on the mean coordinate when calculated. Therefore, in cases like the ostrich, which spent a significant proportion of their time along the northern edge of the paddock, this significantly skews the output and limits the usefulness of these tools in this specific case. For cases such as this, using methods that narrow the dataset will be the best option to obtain usable interpretations. SDEs and KDEs such as displayed in Figures 2(D) and 4 do not expand beyond the boundaries as much and still provide valuable insights into the space use of the target species. Understanding the limitations that restrict the movements of the animals in question is a key requirement when examining the movement of animals. For in-situ species these "limiting factors" can be physical boundaries such as fences (Holloway 2020), lack of environmental/physiological requirements (Traweger and Slotta-Bachmayr 2005) or the inability to cross geographic barriers (Reddy et al. 2019). While the limiting factor in captivity will be the enclosure restrictions in most cases, this does not prevent the use of GIS tools in assessing space use, it simply creates an opportunity for innovation and technique refinement.

Concurrently, the adaptation and development of these methodologies to captive species has potential to improve the quality of modelling tools used for wild animals. For example, the provision of large datasets of extremely fine-scale temporal and spatial data that can be collected in ex-situ locations may be used to test and improve existing methods, as well as support the development of new multi-faceted approaches to behaviour and movement. Moreover, Laube and Purves (2011) display how cross-disciplinary animal research can be used to improve existing technology and methods by examining the quality of GPS units using the movement of cows kept in an agricultural setting. Using

fine-scale data, the authors identified limitations in common methods. This highlights the potential of ex-situ populations to validate findings from tools and methods employed on in-situ populations, which can support conservation decisions.

The Kernel Density Estimators gave the most comprehensive view of the data overall, by displaying the presence and absence of the data as well as the relative density of areas to each other (Figure 4). The KDEs are not without limitations, as they rely on the user to set the best fit radius for the calculation of density (Wand and Jones 1995). For this research, the density was set to 5 m, and it is evident, comparing the different enclosures in figure 4, that this results in the enclosure size causing different scaled KDE outputs and drastically different maximum values of point density for the legend in Figure 4. Scaling the radius with the size of the enclosure in mind will provide the best results (Chen 2015; 2017). Across this dataset, nearly all of the KDE outputs have a large percentage of the enclosure coloured in grey, indicating the presence of animals was recorded, but that animals were reported in low densities. Each animal has only a handful of areas with more colouration, indicating a high density of recorded data points. This is particularly useful for determining species-specific needs and assisting in providing necessary changes for all the animals in an enclosure. From this dataset for example, the SDs and SDEs indicate significant overlaps across species. The KDEs give a more detailed breakdown of the areas of preference and show that while the animals spend much time in similar areas, they still tend to have specified areas of the enclosure they frequent. This information could inform decisions such as species-specific environmental enrichment interventions.

One other potential limitation to be considered in using this type of analysis may come from the size of the target enclosure itself. Zoological institutions contain more than just the large charismatic mammal species. Many zoos are now being encouraged to increase the number of species in their care that require much less space and therefore have considerably smaller enclosures (Keulartz 2023). This may have an impact on the ability of researchers to use the methodologies described in this article, particularly when translating data as described in appendix two. When digitising data from very small enclosures, or enclosures that are housed indoors and are not visible on satellite maps, the GIS user may need to use some creativity to adapt these methodologies to their purposes. This may involve georeferencing building blueprints first and subsequently using this layer as the base for georeferencing an enclosure map, or else potentially manually creating the required polygon and point data layers in QGIS that can be representative of the collected dataset but scaled up to be used in QGIS. There may also be potential to explore new collaborative efforts with advances in indoor mapping such LIDAR or indoor positioning via WiFi signals (Gunduz et al. 2016). Overall, the methods explored in this article may not be a one-size fits all solution to implementing GIS in zoological institutions but does present an opportunity to advance beyond the current standard practice.

This research addresses a key limitation of zoo research, namely the dearth of spatial digital data (Brereton 2020). The use of ZooMonitor and the development of instructional guidelines (Appendix 2) will allow the exploration of space use data in more detail using GIS technology. By expanding beyond traditional methods and establishing new interdisciplinary approaches between GIS and zoo science, novel insights can be achieved, enhancing and driving the progress of zoological institutions. While mSPI has been the focus of this article, other tools are currently used to interpret space use of zoo animals. One not addressed in this article but worth mentioning, is the Electivity Index, which is similar to mSPI, however it produces results for each pre-defined zone of an enclosure, giving the user a measure of how much each zone is visited by an animal or a group in

relation to the other enclosure zones (Brereton and Fernandez 2022; McConnell et al. 2022; Ross et al. 2009). This type of data and inferential analysis can be used across species and enclosure types to help make decisions regarding shelter or feeding locations, environmental enrichment installations, visitor viewing platforms, shelters providing shade, as well as any other spatial decisions that arise during the development and maintenance of zoo enclosures. The design of enclosures and captive animal exhibits has come a long way in the history of animals being kept in captivity, but more advancement can continue to be made (Lawrence et al. 2021). Developing more naturalistic and suitable enclosures for animals while simultaneously ensuring the visitor experience is not diminished is a difficult endeavour for those in the zoo community (Beer et al. 2023). By making use of all the tools available to management and husbandry teams, these decisions can be made from a place of informed understanding of the needs that the animals in care require.

Enclosure design can be related directly to animal health and wellbeing, with enclosure complexity having both positive and negative impacts on variables used to establish welfare statuses, such as behaviour and physical health (De Azevedo et al. 2023). Using tools such as those described here, research can aid other project designs in identifying enclosure design elements that pose potential difficulties for animals. Identifying the paths that animals take through their enclosure may identify features that are avoided or features to which the animals are drawn. One example of this could be assessing mobility concerns in older animals and identifying enclosure elements that have a potential to cause injury (Krebs et al. 2018; Neal Webb et al. 2019). Understanding how an animal's physical capabilities impact their use of their environment and combining this with behavioural research and husbandry practices will lead to better advances in the care of aging individuals, allowing them to continue living an enriched life in captivity.

Looking ahead, further work is required to examine the potential applications of integrating behaviour and social variables into the output of these types of models. Exploring the behaviour of captive species is a key component of modern husbandry practices (Keulartz 2023; Miller and Chinnadurai 2023; Parry-Howells et al. 2023). Combining the spatial analysis methods used in this article and other available metrics, alongside developing areas of research such as coding the behaviour of animals from tri-axial movement loggers (Pavese et al. 2022; Wang 2019), could build new, groundbreaking ways of improving the welfare of captive species through increased understanding of their needs. Similarly, many species held in captivity are kept in social groups. Managing the inter-personal relationships and understanding where potential conflicts may arise, leading to negative impacts on welfare, is a key focus of caregivers in zoos and aquariums. Incorporating social metrics into spatial analysis, such as dyadic interactions or social networking models, may elicit new views of these relationships allowing for better understanding and care to be provided (Grasso et al. 2022; Koyama and Aureli 2019; Rose and Croft 2020; Williams et al. 2023; 2020). Furthermore, the benefit of collecting high quality fine-scale data in an enclosed environment provides the opportunity for testing and validating methodologies used for advising conservation goals and plans. This opportunity can ensure that resources are appropriately invested into the most effective methodologies and prevents the waste of valued time and financial investment in projects that are based on methods that are inadequately developed and tested. Overall, the potential benefits of using GIS tools for captive animal data are yet to be determined in their entirety and can only be discovered when zoological institutions begin to incorporate these techniques into their regular routines and apply tools like those discussed in this article to practical examples.

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