

Article

Detecting and Visualizing Observation Hot-Spots in Massive Volunteer-Contributed Geographic Data across Spatial Scales Using GPU-Accelerated Kernel Density Estimation

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Abstract: Volunteer-contributed geographic data (VGI) is an important source of geospatial big data that support research and applications. A major concern on VGI data quality is that the underlying observation processes are inherently biased. Detecting observation hot-spots thus helps better understand the bias. Enabled by the parallel kernel density estimation (KDE) computational tool that can run on multiple GPUs (graphics processing units), this study conducted point pattern analyses on tens of millions of iNaturalist observations to detect and visualize volunteers' observation hot-spots across spatial scales. It was achieved by setting varying KDE bandwidths in accordance with the spatial scales at which hot-spots are to be detected. The succession of estimated density surfaces were then rendered at a sequence of map scales for visual detection of hot-spots. This study offers an effective geovisualization scheme for hierarchically detecting hot-spots in massive VGI datasets, which is useful for understanding the pattern-shaping drivers that operate at multiple spatial scales. This research exemplifies a computational tool that is supported by high-performance computing and capable of efficiently detecting and visualizing multi-scale hot-spots in geospatial big data and contributes to expanding the toolbox for geospatial big data analytics.



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Keywords: volunteered geographic information (VGI); geospatial big data; point pattern analysis; kernel density estimation; hot-spot detection and visualization; spatial bias; multiple spatial scales; iNaturalist; graphics processing unit (GPU); parallel computing

1. Introduction

Volunteer-contributed geographic data, often termed 'volunteered geographic information' (VGI) [1], have flourished over the past two decades or so due to the vast advancements in geospatial and communication technologies (e.g., location-aware smart phones, social media) that enable ordinary citizens to collect and share georeferenced observations of the world [2]. Broadly speaking, VGI encompasses geographic data generated and shared (actively or passively) by volunteers participating in geographic citizen science, participatory mapping, public participation geographic information systems, neogeography, social media, crowdsourcing, etc. [2]. Prominent VGI examples, among others, include OpenStreetMap, a platform for volunteers to collaboratively map all kinds of geographic features across the globe with great details [3], and biodiversity citizen science projects such as eBird and iNaturalist to which nature observers submit tens of thousands of species sightings on a daily basis [4,5]. Notably, citizen science [6] has existed for centuries, and geographic citizen science [7,8] has been a major source of volunteer-contributed geographic data (e.g., biodiversity observations), even long before the term VGI was coined in 2007 [1]. VGI has risen to become an important source of geospatial data supporting scientific research and applications (e.g., biodiversity monitoring, disaster response) largely due to its low cost, extensive coverage, high spatiotemporal resolution, and data update timeliness [9–13]. In a larger context, VGI represents a paradigm shift in how geographic data is created and shared and in its content and characteristics [14]. It may have great

influence on geography and its relationship to society [1,15]. VGI (particularly citizen science), due to its active engagement of the general public in scientific research activities (e.g., data collection), is regarded as a bridge between geography (and other disciplines) and society that helps harness the power of the public to advance scientific discoveries through carefully designed projects [16] and, at the same time, increase scientific awareness of the public [17,18]. In fact, VGI is an important source of geospatial big data which is propelling geographic research towards emerging paradigms such as ‘data-driven geography’ [19] and ‘data-intensive science’ [20].

VGI data quality issues, nonetheless, are under constant scrutiny [21]. Spatial data collected and shared by volunteer communities may or may not be as of high quality as data compiled by professional agencies. Data quality therefore is always an important consideration when using VGI for any applications. A variety of methods and frameworks have been proposed for assessing VGI data quality from the perspectives of source credibility [22,23] and the fundamental dimensions of spatial data quality (positional accuracy, attribute accuracy, temporal accuracy, semantic accuracy, logical consistency, completeness, and lineage) [24–31], and for assuring VGI data quality [24,32–35]. Despite the quality assessment or assurance measures, VGI datasets are often subject to various forms of biases (e.g., spatial bias, temporal bias, demographic bias) [21,36–38]. A useful first step towards better understanding such biases is simply visualizing where VGI observations were originated, as the spatial distribution of VGI observations has implications on ‘representativeness’ of the resulted VGI datasets [36]. Individual volunteers driven by self-interest or self-motivation often choose sites for observation on their own, in contrast to traditional geographic data collection efforts conducted by trained professionals following established protocols and geographic sampling schemes (e.g., stratified random sampling) [39]. It is widely recognized observation efforts of volunteers tend to concentrate in certain geographic areas (e.g., areas of better accessibility) and VGI datasets, as a result, are often spatially biased [40–42].

Examining the spatial pattern of volunteers’ observation efforts can shed light upon the driving spatial processes that often operate at multiple spatial scales [37]. A better comprehension of the patterns in observation efforts across spatial scales helps understand the inherent spatial biases embedded in VGI datasets, and could also inform devising appropriate bias mitigation strategies [43–46]. Geographic locations where volunteers conducted observations can be taken as a spatial point pattern consisting of point events (i.e., observation was conducted at individual locations). Therefore, spatial point pattern analysis [47], a classic spatial analysis method widely used across many domains (e.g., geography, ecology, spatial epidemiology, crime analysis, and traffic accident analysis), can be applied to detect any interesting spatial patterns in volunteer’s observation efforts.

Kernel density estimation (KDE) is a common approach to explanatory spatial point pattern analysis [47,48]. It is capable of estimating a continuous probability density surface of the point event over geographic space based on a set of discrete sample event locations [49]. The density surface can be used to detect and visualize event hot-spots (i.e., clusters) to facilitate qualitative investigation of the point pattern. Moreover, hot-spots in the point pattern can be detected and visualized at varied spatial scales with the KDE approach by setting appropriate kernel bandwidths, a parameter controlling the smoothness (i.e., level of generalization) of the estimated density surface [49–51]. Furthermore, the density surface serves as a basis for conducting further quantitative analysis, for instance, delineating cluster zones [51,52] and testing statistical significance through Monte Carlo simulations [47], and correcting for geographic sampling bias [44]. Such characteristics render the KDE approach desirable for visualizing and analyzing spatial patterns in volunteer’s observation efforts.

Applying the KDE approach on massive VGI datasets, however, faces computational challenges [50,51]. First, as the number of data points (i.e., locations) increases (e.g., millions or even billions of locations), there are significant computational costs associated with simple spatial queries (e.g., finding nearby locations to compute their kernel density

contributions towards a foci location). Second, determining the optimal kernel bandwidth (s) for KDE is computationally intensive as the iterative optimization process involves iterations of complex computations [49]. Lastly, computing kernel density based on numerous data points on a high-resolution grid of raster cells over extensive geographic area is computationally expensive. As a result, traditional software tools implementing the KDE method are not able to handle massive datasets.

Until recently, high-performance computational tools have been developed to enable point pattern analysis on geospatial big data [53–55], especially with the KDE method [50,51]. The tools utilize spatial indexing techniques such as k-dimensional tree and quad-tree to speed up spatial queries, implement algorithmic optimizations to reduce computational complexity, and adopt parallel computing on multi-core CPUs (central processing units) or many-core GPUs (graphics processing units) to further accelerate KDE computations. As a result, these newly developed high-performance computational tools have made it feasible to complete point pattern analysis on massive point event datasets within a reasonable amount of time. The largest experiment datasets used to test computing performance of the tools contain about one million point locations [50,51].

Empowered by the big data-enabled point pattern analysis tools, this study aims to detect and visualize multi-scale observation hot-spots in massive volunteer-contributed geographic data (e.g., tens of millions of points) to the global extent using the KDE method accelerated with GPU parallel computing [50]. This endeavor advances understanding of the spatial pattern of VGI contributor's data contribution activities, sheds light upon the inherent spatial biases in global-coverage VGI datasets at various spatial scales, and ultimately informs designing proper methods to mitigate the impacts of such biases when VGI is used in spatial analysis and modeling (e.g., species distribution modeling).

To the best of the author's knowledge, this is the first attempt to detect and visualize VGI contributors' observation hot-spots across spatial scales on a global scale using the KDE approach. Existing efforts of visualizing spatial patterns in large-scale VGI datasets avoided the KDE approach despite its advantages for both visualization and quantitative analysis and, instead, adopted other less computationally demanding methods for faster on-the-fly visualization. For instance, eBird (ebird.org/hotspots, accessed on 6 January 2022) and iNaturalist (www.inaturalist.org/observations, accessed on 6 January 2022) both adopt a quadrat-based approach to simply count the number of observations (i.e., intensity) within a grid of rectangular quadrats for visualizing observation hot-spots in data submissions. Although the quadrat-based approach can visualize hot-spots at multiple spatial scales by adjusting quadrat size depending on the current viewing zoom level, it introduces artificial abrupt intensity change across quadrat boundaries and, more importantly, quadrats delineation is subject to the modifiable areal unit problem [56,57]. The KDE approach would overcome such drawbacks [58] as continuous probability surfaces estimated with scale-dependent kernel bandwidths are used to detect and visualize multi-scale observation hot-spots. This study examines the applicability and usefulness of the KDE method for analyzing massive point datasets for hot-spot detection and visualization, using VGI datasets with over 30 million points obtained from iNaturalist as an example. The remainder of this article is organized as follows. Section 2 introduces data and methods, Section 3 presents results and related discussion, and Section 4 concludes the article.

2. Materials and Methods

2.1. Datasets

2.1.1. VGI Data

VGI datasets containing locations where volunteers conducted observations were obtained from iNaturalist, the world's largest citizen science project (in terms of the number of participants) with global coverage aiming to engage nature observers in uploading, identifying, and sharing species observations of all taxa [5,59]. In this study, iNaturalist was used as an example to illustrate the usefulness of the GPU-accelerated KDE approach for visualizing multi-scale observation hot-spots in massive VGI datasets, although the

approach itself is applicable to any spatial point datasets. Users upload geo-referenced and time-stamped photos of species observations, along with auxiliary information (e.g., suggested species identification) through the iNaturalist website or mobile app. Users can also choose whether to obscure the observation's geographic coordinates (latitude and longitude) to protect geoprivacy (if obscuring, the observation location is replaced with a random location selected from a 0.2° latitude $\times$ 0.2° longitude cell containing the true location), and whether to make a submission public and hence visible to the community of contributors. The community collaboratively identify or confirm species for public observations through a voting mechanism. As of November 2021, nearly 2 million contributors have contributed over 85 million observations on more than 345,000 species around the world [60]. All public observations are available on the iNaturalist website for download (www.inaturalist.org/observations/export, accessed on 6 January 2022). Observations meeting certain data quality criteria are labeled as 'Research Grade' [61] and a dataset containing only such observations are published and updated periodically on the Global Biodiversity Information Facility website [62].

Observations conducted in 2019 and 2020 with latitude between 60° S and 75° N (very few observations were beyond this latitude range) and non-obscured geographic coordinates were downloaded from iNaturalist and loaded into a spatial database. Data in these two years were chosen due to the fact that applying the GPU-accelerated KDE approach to visualize observation hot-spots in individual years makes it feasible to identify any pattern change across the two years. Obscured observations were excluded as they were associated with too high positional uncertainty for meaningful point pattern analysis. Geographically distinct observation locations (i.e., point locations with unique latitude longitude coordinates) were then extracted. The above processing steps resulted in 11,986,484 and 19,022,923 observation locations in 2019 and 2020, respectively. Simply plotting the point locations on a global scale creates visually cluttered point maps that are similar across the two years (Figure 1), although there were 7 million more point locations in 2020 and spatial pattern of the locations might have changed over the years, e.g., due to the ongoing COVID-19 pandemic [10]. With such point maps, it is difficult to visually detect iNaturalist contributors' observation hot-spots in a single year across spatial scales, nor visually identify any spatial pattern change over time.

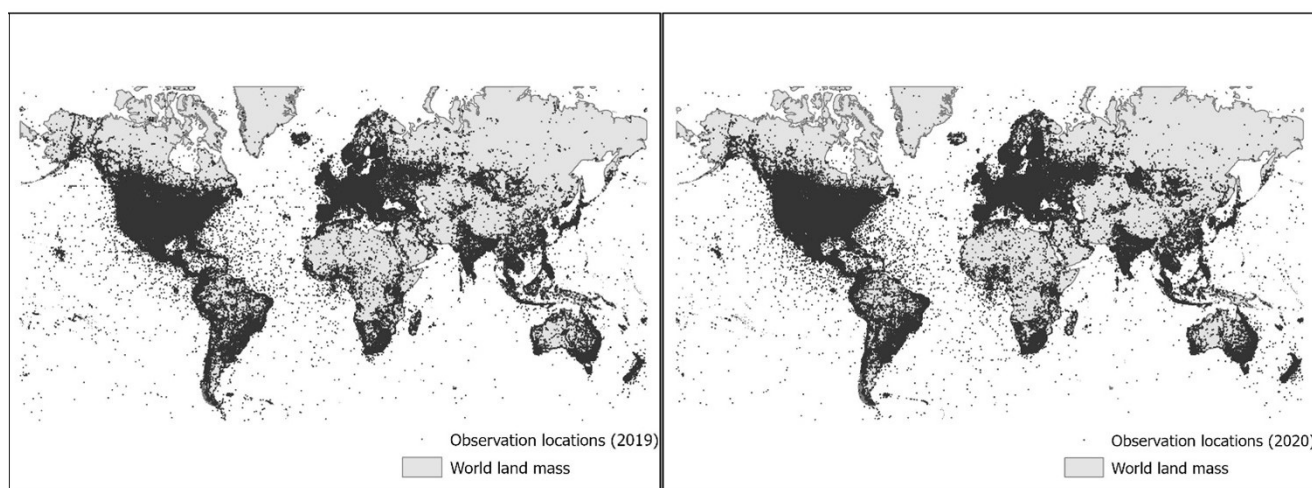


Figure 1. iNaturalist observation locations in 2019 (left) and 2020 (right).

2.1.2. Land Boundaries

Density surfaces in this study were estimated only for the world's land areas for hot-spot detection and visualization, as the vast majority of iNaturalist observation locations are on land and excluding oceans greatly reduces KDE computational workload. The 1:10 million land polygons (including major islands) downloaded from the Natural Earth

website (www.naturalearthdata.com (accessed on 13 September 2021)) were used to depict boundaries of the world's land mass. The land polygons were converted to rasters at varied spatial resolutions (5 km, 1 km, 500 m, etc.) for estimating density surfaces.

2.2. Methods

The KDE approach to exploratory point pattern analysis, accelerated with parallel computing on GPUs, was adopted to estimate density surfaces for detecting and visualizing observation hot-spots across spatial scales in the massive iNaturalist datasets.

2.2.1. GPU-Accelerated KDE Approach

The KDE approach assumes that an event occurred at a given location X_i could occur at another location x at a lower probability, which is inversely related to the distance from X_i to x . The distance-decaying probability is represented by a kernel function $K(\cdot)$. The typical Gaussian kernel was adopted in this study [63]:

$$K\left(\frac{|x - X_i|}{h_i}\right) = \frac{1}{2\pi} e^{-\frac{|x - X_i|^2}{2h_i^2}} \quad (1)$$

where $|x - X_i|$ is the distance between the two locations, and h_i is the bandwidth parameter controlling how quickly the probability decays as the distance to X_i increases. Conceptually, the kernel can be thought of as a three-dimensional probability density surface (i.e., a bell) with a fixed volume of 1 centered at each sample event location. Bandwidth h_i determines the shape of the kernel at sample location X_i and a larger bandwidth indicates wider but shorter kernel. The KDE method then computes the probability density of the event occurring at any location x as the mean of density contributions from all sample locations [49]:

$$f(x) = \frac{1}{n} \sum_{i=1}^n \frac{1}{h_i^2} K\left(\frac{|x - X_i|}{h_i}\right) \quad (2)$$

where $f(x)$ is the estimated density at location x , and n is the total number of sample locations. Applying Equation (2) to every one of the cell locations in the study area results in a probability density surface.

Smoothness of the estimated density surface is largely influenced by the bandwidths [49,63]. Bandwidths can be the same at all sample locations (fixed KDE). Generally speaking, larger bandwidths tend to smooth out local density variations and the estimated density surface thus could only reveal large-scale density variations. With small bandwidths, KDE is able to reveal local density variations but may fail to capture the general trend. The bandwidth for fixed KDE can be conveniently computed following the simple 'rule-of-thumb' heuristic that takes into account the spatial distribution (i.e., standard distance) of the sample locations [63], or through optimization with the objective of maximizing the likelihood (probability) of observing the event across the sample locations [49]. Bandwidths could also vary across sample locations (adaptive KDE). Adaptive KDE flexibly employs larger bandwidths at sparsely distributed sample locations and smaller bandwidths at dense sample locations, and thus is capable of discern subtle density variations in areas of dense sample locations [49]. Spatially adaptive bandwidths can be determined based on simple heuristics (e.g., K-nearest neighbor distance) [64] or through optimization [49]. In general, determining bandwidth (s) using optimization is much more computationally expensive than using simple heuristics (e.g., 'rule-of-thumb', K-nearest neighbor distance).

When the KDE method is used on very large datasets, determining bandwidths for KDE, especially through optimization, and subsequently estimating the probability density surface (on a fine-resolution raster grid over a large geographic area) can both be computationally demanding [50,51]. To overcome the computational challenges, the GPU-parallel KDE tool developed in [50] enabling point pattern analysis on geospatial big data was adopted to detect and visualize observation hot-spots in the massive iNaturalist datasets.

The original implementation of the KDE tool with parallel computing on multiple GPUs implemented based on the CUDA parallel programming library [65] runs only on a single GPU [50]. This study improved the tool so that it can utilize parallel computing power on any number of GPUs available on the computing platform. The new version (source codes available on GitHub at <https://rb.gy/mv0z5m>, accessed on 26 November 2021) splits KDE computation workload into smaller parts and dispatch them to multiple GPUs to be carried out collaboratively. Besides, the new version implemented the less computationally demanding K-nearest neighbor distance heuristic for determining adaptive bandwidths [64], in addition to the existing option of determining adaptive bandwidths based on optimization [50]. The improvements further expand the upper limit of the problem size of point pattern analysis tasks which the GPU-parallel KDE tool can tackle.

The GPU-parallel KDE tool was run in two computing environments with GPU capabilities to estimate probability density surfaces from iNaturalist observation locations for detecting and visualizing observation hot-spots across spatial scales. One runs Windows Server 2016 (Intel Xeon 24-core CPUs @ 2.7 GHz, 192 GB memory) with a NVIDIA Tesla V100 GPU (32 GB memory). The other has Windows 10 (Intel Xeon 8-core CPUs @ 3.7 GHz, 64 GB memory) and two identical NVIDIA Quadro P4000 GPUs (8 GB memory). The time it took to complete individual density surface estimation tasks ranges from minutes to hours depending on the problem size (e.g., number of observation locations, spatial resolution of the estimated density surface, bandwidth option). Comparisons of the GPU-accelerated KDE tool against KDE tools in existing GIS software were reported in Section 3.4.

2.2.2. Detecting and Visualizing Observation Hot-Spots across Spatial Scales

The bandwidth for KDE controls the smoothness of the estimated probability density surface and hence the spatial scale at which hot-spots can be detected (i.e., level of spatial generalization). Based on this observation, a series of bandwidths in accordance with the spatial scales of hot-spots can be set for the fixed bandwidth KDE method to estimate a succession of density surfaces for detecting and visualizing observation hot-spots across spatial scales (Table 1). Specifically, the ‘rule-of-thumb’ bandwidth ($h_{r.o.t.} = 134,330$ and $124,993$ m for 2019 and 2020, respectively), which often results in an over-smoothed density surface, was used as an initial bandwidth to estimate a density surface for hot-spot detection and visualization at the coarsest spatial scale (e.g., global). The bandwidth was then reduced to $1/2$ of the previous bandwidth to estimate another density surface for detecting and visualizing hot-spots at a finer spatial scale. This process was repeated until the bandwidth was reduced to $1/128$ of the initial bandwidth ($h_{r.o.t.}/128 = 1049$ and 976 m for 2019 and 2020, respectively). Furthermore, an even smaller bandwidth determined through optimization ($h_{opt.} = 493$ and 530 m for 2019 and 2020, respectively) [49] was used to estimate an additional density surface for hot-spot detection and visualization at the finest spatial scale (e.g., neighborhood).

The procession of density surfaces estimated with the KDE method were visualized in ArcGIS Pro [66] with the ‘dynamic range adjustment’ statistics computed from the current display extent and the ‘standard deviation’ stretch type to visually highlight hot-spots on the observation density maps. Each hot-spot map was displayed within only a prescribed range of map scales corresponding to the spatial scale at which observation hot-spots are visually detected. When zooming in and out on the map, hot-spots within the display extent at the current spatial scale were properly rendered for visual inspection. This visualizing strategy was found most informative compared to alternatives (e.g., stretching based on whole-raster statistics) for visually detecting hot-spots in iNaturalist observation locations, as it is capable of rendering hot-spot maps in a manner that is responsive to both display scale and extent.

Table 1. Bandwidths used in fixed-bandwidth KDE for detecting hot-spots across spatial scales. $h_{r.o.t.}$ and $h_{opt.}$ are the bandwidths determined based on the ‘rule-of-thumb’ heuristic and through optimization, respectively. Smaller bandwidths are associated with finer spatial resolutions, larger display map scales, and increasingly fine spatial scales at which hot-spots are detected and visualized.

Bandwidth	Resolution	Display Map Scale	Spatial Scale
$h_{r.o.t.}$	5 km	$\leq 1:40$ million	Global
$h_{r.o.t.}/2$	5 km	$\leq 1:20$ million	Continental
$h_{r.o.t.}/4$	5 km	$\leq 1:10$ million	Regional
$h_{r.o.t.}/8$	1 km	$\leq 1:5$ million	Country
$h_{r.o.t.}/16$	1 km	$\leq 1:2.5$ million	States
$h_{r.o.t.}/32$	500 m	$\leq 1:1.2$ million	Metropolitan
$h_{r.o.t.}/64$	500 m	$\leq 1:600,000$	City
$h_{r.o.t.}/128$	100 m	$\leq 1:300,000$	Sub-city
$h_{opt.}$	100 m	$\leq 1:180,000$	Neighborhood

In addition, a web map for visually detecting observation hot-spots across spatial scales was published through the ArcGIS Online platform [67]. Map tiles rendering multi-scale observation hot-spots across a sequence of map zoom levels (i.e., display map scales) were created using the Create Map Tile Package geoprocessing tool in ArcGIS Pro. The tile packages were then uploaded to ArcGIS Online and published as a web map that can be viewed freely at <https://rb.gy/1cjyey>, accessed on 26 November 2021. Zooming in and out triggers the web map to load tiles at the proper zoom level for visualizing observation hot-spots across spatial scales.

3. Results and Discussion

3.1. Visual Detection of Observation Hot-Spots across Spatial Scales

Globally, North America and Europe are the two largest iNaturalist observation hot-spots in the world (Figure 2A). Western Europe and eastern, western, and southern United States are obvious regional observation hot-spots. European countries such as the United Kingdom, Germany, Belgium, Netherlands, Switzerland, and Italy, and US states including California, Washington, Texas, Florida, Maryland, New Jersey, New York, Connecticut, and Massachusetts stand out as country- or state-level hot-spots. At a finer spatial scale, iNaturalist observation hot-spots well coincide with large metropolitan areas (e.g., San Francisco, Los Angeles, Dallas, Denver, Chicago, Minneapolis, New York, Mexico City, Quito, London, Milan, Madrid, Moscow, Cape Town, Sydney, Melbourne, Hong Kong, Tokyo, and Seoul). Observation hot-spots are also detected at finer scales. For example, within the Denver metropolitan area (Figure 2), city- to neighborhood-level observation hot-spots (e.g., in parks, along trails) are readily visible on the density maps with increasing spatial details.

Visualization of the kernel density raster maps in ArcGIS Pro and on the ArcGIS Online web map (<https://rb.gy/1cjyey>, accessed on 26 November 2021) can be utilized to visually detect observation hot-spots across spatial scales in iNaturalist data for any part of the world (e.g., from global to neighborhood scales). Such a geovisual tool for hierarchically detecting and visualizing observation hot-spots across spatial scales in massive VGI datasets offers many benefits, as discussed in more detail in Section 3.3.

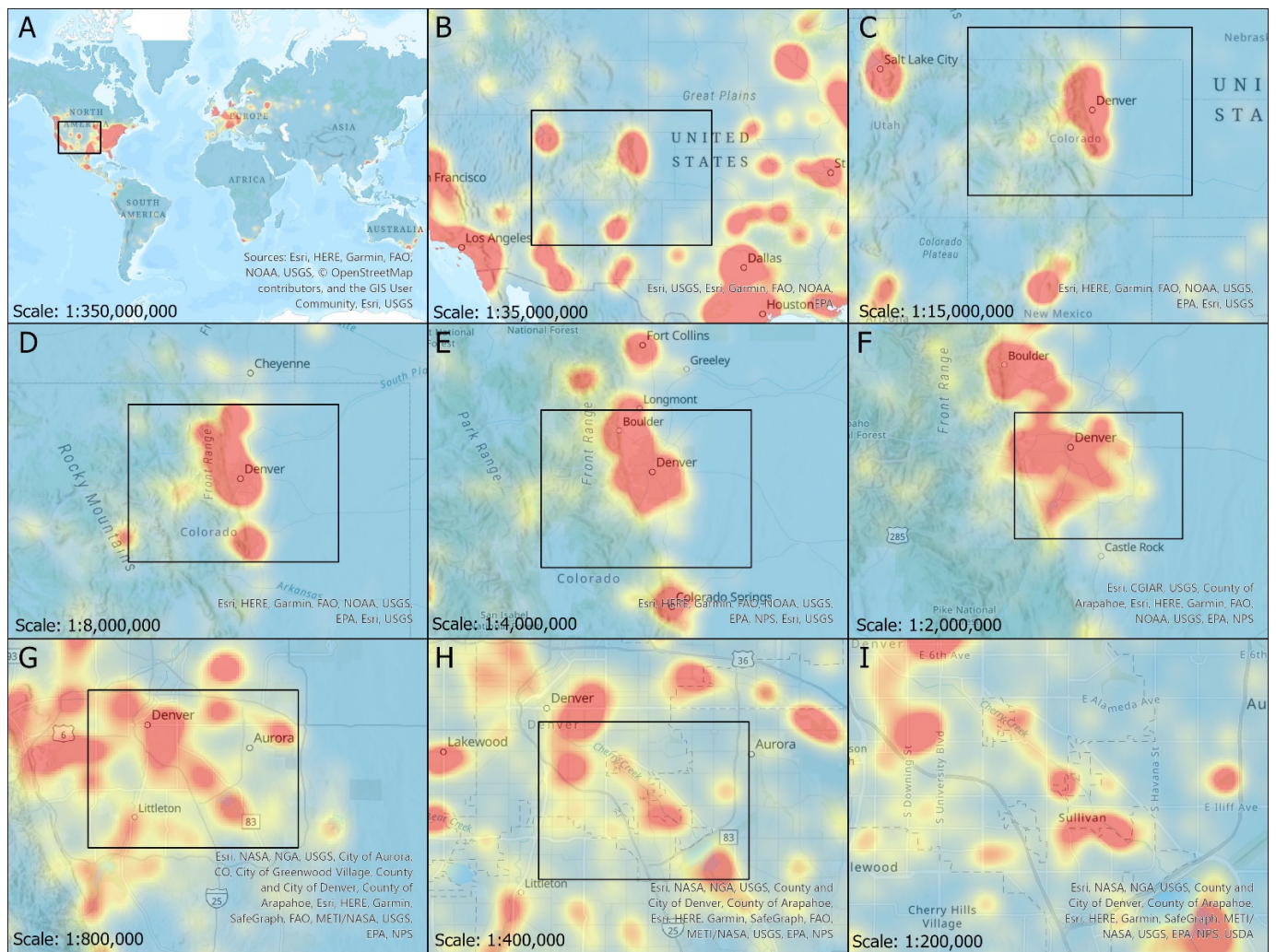


Figure 2. iNaturalist observation hot-spots (2020) in the Denver metropolitan area across spatial scales. (A–I) corresponds to the increasingly large map scales at which hot-spots are detected and visualized. On each map, red color represents high observation density, and the inner box indicates the display extent of the next map in sequence rendering finer-scale hot-spots.

3.2. Hot-Spot Detection and Visualization at Even Finer Spatial Scales

The KDE approach can be conveniently adopted to detect observation hot-spots at even finer spatial scales (e.g., block- or street-scale), shall there be a need, for example, for understanding VGI contributor's observation site selection behavior in a micro-environment. For this purpose, bandwidths determined through optimization were used in the KDE method to reveal subtle density variations at micro-scales [49,50] in selected areas of interest. The bandwidths, either fixed or adaptive, were optimized on only a local subset of observation locations that are within the area or within certain distance from the area boundary (e.g., 10 km), as bandwidths optimized on the global datasets still produced over-smoothed density surfaces that could not reveal density variations at micro-scales (e.g., Figure 3I).

Figure 3 shows the resultant density maps at 10-m spatial resolution for one area of interest (Cherry Creek State Park in Denver) estimated with fixed bandwidth (Figure 3J) and adaptive bandwidths (Figure 3K) determined through optimization. The very high spatial resolution of the density surface coupled with locally optimized bandwidths allows detecting and visualizing observation hot-spots at very fine spatial scales. For example, whilst the density map estimated with globally optimized fixed bandwidth (Figure 3I) only reveals one large hot-spot on the south end of the reservoir in the park, the map estimated with locally optimized fixed bandwidth (Figure 3J) further distinguishes two

smaller hot-spots (one hot-spot on the southeast side and another larger hot-spot on the southwest side), and the map estimated with locally optimized adaptive bandwidths (Figure 3K) was able to detect and visualize several hot-spots with more precise spatial extent. Detecting and visualizing hot-spots at such fine spatial scales provides useful information for understanding volunteer's observation preferences in a micro-environment (e.g., more observations were concentrated in the woods along the east shore) (Figure 3K).

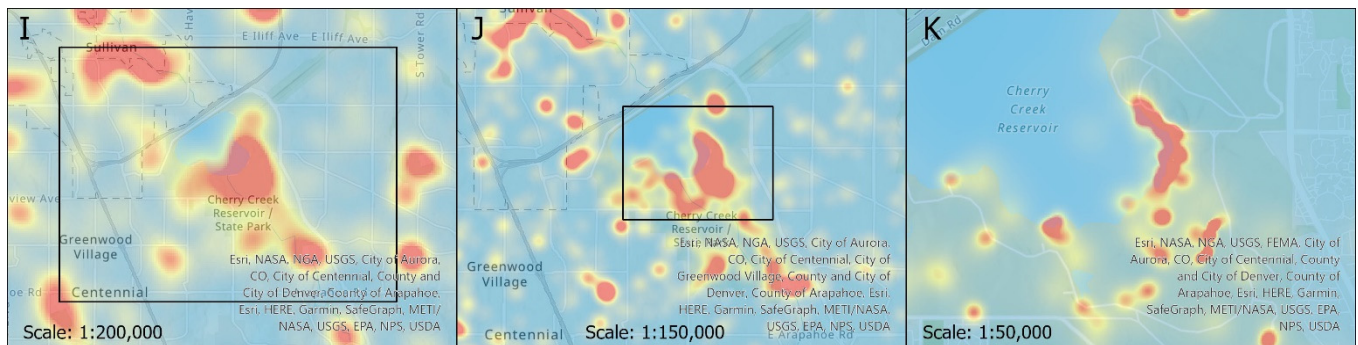


Figure 3. Observation hot-spots (2020) detected and rendered at micro-scales in a park in Denver. (I–K) corresponds to the increasingly large map scales at which hot-spots are detected and visualized.

3.3. Usefulness for Exploratory Point Pattern Analysis and Beyond

Backed by the GPU-accelerated KDE tool, the proposed scheme for hierarchical detection and visualization of hot-spots within massive point datasets across spatial scales offers a powerful geovisual tool for exploratory point pattern analysis, which enables formulating hypotheses to uncover the spatial processes that operate at multiple spatial scales to have shaped the point pattern [47,58]. Intuitions regarding the multi-scale pattern-shaping spatial processes are easier to develop from visually exploring the hot-spot maps across spatial scales and comparing the hot-spot maps against maps depicting the spatial variation of environmental and cultural factors that could play a role in shaping the patterns (e.g., population density, land cover, accessibility to mobile technologies). For instance, continental-, regional-, and country-scale observation hot-spots in VGI datasets may be mainly attributed to cultural and socio-economic factors. As explored in [37], nature observing has a longer history and is a more popular activity in western English-speaking countries, which are also on the high end of United Nations Human Development Index (e.g., longer life expectancy, more years of education, higher gross national income per capita). States, metropolitan, and city-scale observation hot-spots, reflecting an urban-rural divide, could be linked mostly to human population distribution, infrastructure availability (e.g., road, Internet), and by extension, the digital divide [37,68]. For sub-city- to neighborhood-level observation hot-spots, however, the dominant driving factors may be more related to human behavior patterns. For example, people tend to report species sightings in open green spaces such as parks, botanic gardens, and trails [37] while enjoying the benefits of human-nature interactions [69]. Such intuitions could well inform formulating hypotheses to explain the hot-spot patterns across spatial scales. Beyond, they are also informative for devising methodologies to model sampling biases in VGI observations [37], which could be a basis for correcting for such biases when VGI observations are used in spatial analysis and modeling [12,70,71].

The hot-spot maps could also be used to discover point pattern change over time. Visually comparing hot-spot maps at the same spatial scale but from different times helps qualitatively identify changes in spatial pattern across time and facilitates understanding the underlying causes. As an example, Figure 4 shows hot-spot maps on the University of Denver (DU) campus in 2019 and 2020. There was a large hot-spot on campus in 2019 but it was no longer the case in 2020. This change was due to that the DU Nature Challenge, an annual event where participants survey biodiversity on DU campus and report species observations to iNaturalist, was cancelled due to the ongoing COVID-19 pandemic. More broadly, the visualizations are helpful for identifying observation hot-spot

pattern change across spatial scales to reveal impacts of the pandemic on VGI contributors' data contribution patterns. It could offer new evidence to consolidate findings regarding COVID-19 effects on citizen science projects and therefore contribute to forming guidelines on how to account for data anomalies caused by the pandemic [72–75].

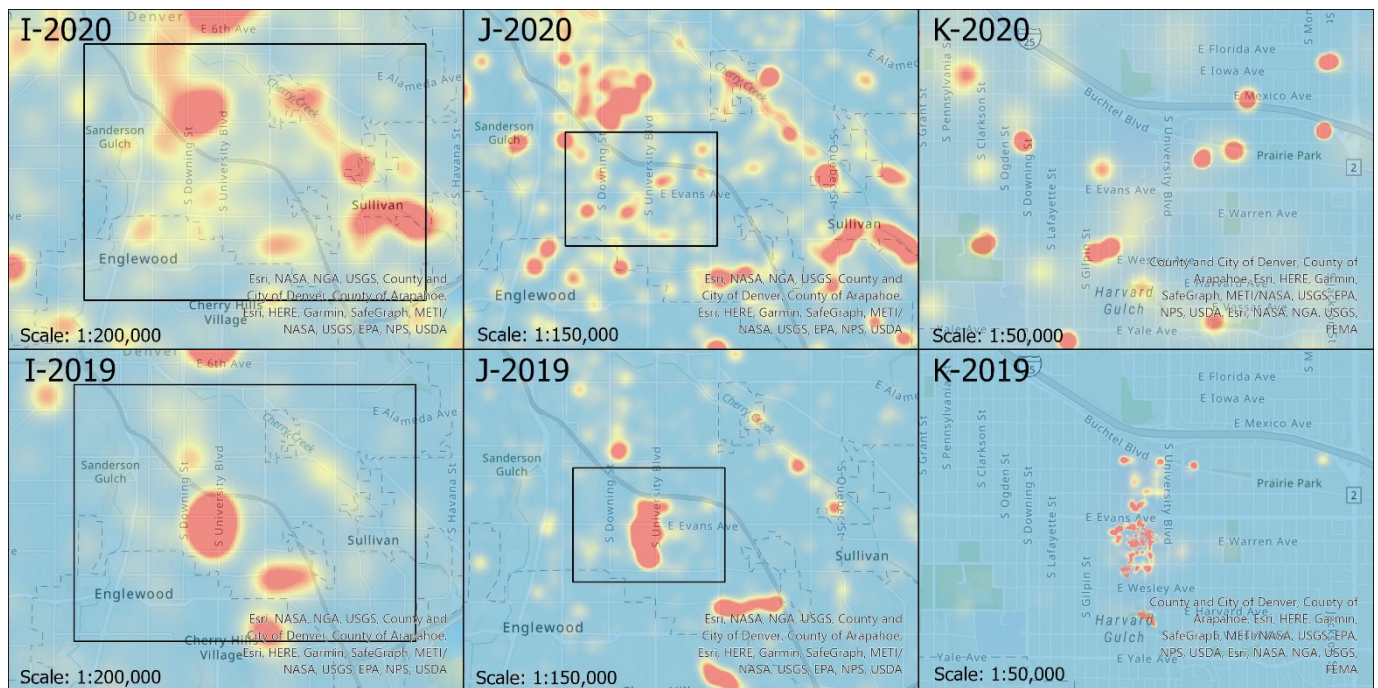


Figure 4. Changes in observation hot-spots across 2019 and 2020 on the University of Denver campus. (I–K) corresponds to the increasingly large map scales at which hot-spots are detected and visualized.

This study used only iNaturalist data in two individual years (2019 and 2020) to demonstrate the usability and usefulness of the GPU-accelerated KDE tool and the geovisualization scheme (Section 2.2.2) for visualizing hot-spots in point data across spatial scales and identifying yearly pattern change. A full investigation regarding what have shaped the hot-spots and what have caused pattern change in iNaturalist observations is out of the scope of this article and deserves a separate treatment (an example of such studies can be found in [37]). Nonetheless, one could easily apply the GPU-accelerated KDE tool and the geovisualization scheme with customized spatial and temporal resolutions (e.g., weekly, monthly) on other (big) point datasets to visualize multi-scale hot-spots and identify any pattern change as a starting point for answering research questions pertinent to the specific datasets.

3.4. Comparison of the GPU-Accelerated KDE Tool and KDE Tools in Existing GIS Software

The GPU-accelerated KDE tool used in this study was compared with KDE tools in existing GIS software, specifically, the proprietary ArcGIS Pro (version 2.9) [66] and the open-source QGIS (version 3.22) [76]. KDE results are known to be more sensitive to the bandwidth than to the kernel function [63]. The KDE tool in Pro implemented the Quartic kernel function with a ‘rule-of-thumb’ algorithm to calculate a default bandwidth based on the standard distance of the points. The KDE tool in QGIS does not compute a default bandwidth (i.e., user must specify a bandwidth) for any of the five implemented kernel functions (Quartic, Triangular, Uniform, Triweight, Epanechnikov). Moreover, both tools implement only fixed-bandwidth KDE with no support for adaptive-bandwidth KDE. Compared to KDE with a fixed bandwidth, KDE with adaptive bandwidths can better reveal subtle density variations in areas of dense point events (e.g., Section 3.2) [49,50]. For example, when applying KDE to analyze disease cases, the bandwidth can be set to

inversely relate to population density to account for inhomogeneous background [77,78]. In this regard, the GPU-accelerated KDE tool is superior to the KDE tools in Pro and QGIS, as it supports both adaptive-bandwidth KDE and fixed-bandwidth KDE and it implemented (parallelized) algorithms to automatically determine the optimal bandwidths for the Gaussian kernel function (Section 2.2.1) [50].

Another important consideration is computing performance and scalability of the KDE tools on point pattern analysis tasks involving large datasets (e.g., estimating a high-resolution density surface over a large study area from a large number of points). The KDE tool in QGIS runs on only a single CPU thread, the KDE tool in Pro can be configured to run on either a single CPU thread or multiple CPU threads (i.e., utilizing parallel computing on multi-core CPUs), and the GPU-parallel KDE can exploit parallel computing power on GPUs. To empirically evaluate the computing performance of the KDE tools, they were applied on the 2019 iNaturalist data. Although the estimated density surfaces reveal similar hot-spot patterns on the global scale (Figure 5), the execution time of the tools differ drastically (Table 2). The QGIS tool is very slow even on relatively small datasets (e.g., densities were estimated at 5 km spatial resolution). It thus would not be useful on large datasets. On small datasets, the Pro tool runs faster than the GPU tool. On larger datasets (e.g., densities were estimated at 1 km or 500 m resolutions), the GPU tool is much faster than the Pro tool, although running the latter on eight threads could speed up computations by three to four times. Moreover, the GPU tool scales much better than the Pro tool on large datasets. For example, when estimation resolution increases from 1 km to 500 m, execution time of the Pro tool has a three- to four-fold increase, whilst execution time of the GPU tool increases only by a factor of 1.3. Overall, the GPU-accelerated KDE tool is more efficient and flexible for conducting KDE tasks involving large datasets.

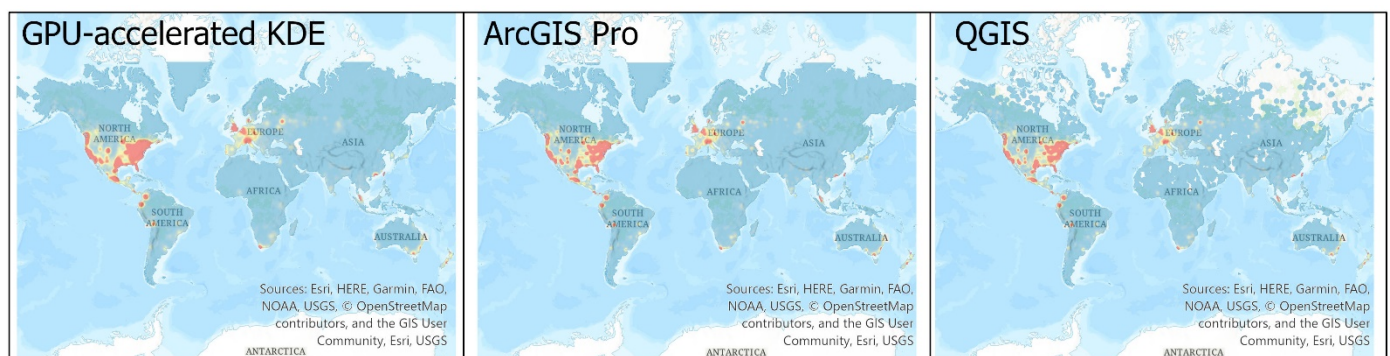


Figure 5. Density surfaces (5 km resolution) estimated using the GPU-parallel KDE tool (Gaussian kernel; default bandwidth = 134,330 m), and using the KDE tools in ArcGIS Pro (Quartic kernel; default bandwidth = 250,891 m) and in QGIS (Quartic kernel, bandwidth = 250,891 m).

Table 2. Execution time of the KDE tools to estimate density surfaces at varied spatial resolutions using the 2019 iNaturalist data ($n = 11,986,484$ points) with a fixed bandwidth. Higher spatial resolution represents KDE task involving larger datasets. The KDE tool in Pro were run with both one thread and eight threads. Experiments were conducted on the server computer running Windows Server 2016 with a NVIDIA Tesla GPU.

KDE Tool	Resolution	Execution Time	
QGIS	5 km	5 h 40 min 2 s	
GPU-parallel KDE	5 km	7 min 11 s	
	1 km	7 min 51 s	
	500 m	10 min 5 s	
ArcGIS Pro	5 km	1 thread	8 threads
		5 min 10 s	1 min 15 s
	1 km	1 h 33 min 20 s	18 min 11 s
		5 h 51 min 51 s	1 h 9 min 3 s
	500 m		

4. Conclusions

Enabled by the multi-GPU parallel KDE computational tool, this study presents a geovisualization scheme to conduct point pattern analyses on massive VGI datasets (e.g., tens of millions of iNaturalist observations with a global coverage) for detecting and visualizing volunteers' observation hot-spots across spatial scales. It was achieved by setting varying bandwidths for the KDE method in accordance with the spatial scales at which hot-spots are to be detected (e.g., from continental to neighborhood and even finer scales) to estimate a succession of density raster surfaces. The density rasters were then rendered and displayed at a sequence of map scales for visually detecting hot-spots. The geovisualization scheme built upon the GPU-accelerated KDE tool offers a hierarchical mechanism for visualizing volunteers' observation hot-spots in massive data across spatial scales. It effectively facilitates visually detecting observation hot-spots and identifying pattern changes over time. As an exploratory data analysis tool, it is helpful for exploring the underlying drivers that have shaped the pattern in volunteer's observation efforts and the causes of any pattern change. One can easily apply the GPU-accelerated KDE tool and the geovisualization scheme to other big point datasets (not necessarily VGI data) to visualize multi-scale hot-spots and identify any pattern change as a starting point for answering research questions pertinent to the datasets. This research exemplifies a high-performance computing-backed and big data-capable tool for conducting exploratory point pattern analysis on massive point datasets. It is an invaluable addition to the expanding toolbox for geospatial big data analytics.

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