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Opinion

Quantitative conservation geography

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Ongoing biodiversity loss represents the erosion of intrinsic value of living nature, reduces the contributions nature provides to people, and undermines efforts to move towards sustainability. We propose the recognition of quantitative conservation geography as a subfield of conservation science that studies where, when, and what conservation actions could be implemented in order to mitigate threats and promote sustainable people–nature interactions. We outline relevant methods and data needed in quantitative conservation geography. We also discuss the importance of filling information gaps, for example by using emerging technologies and digital data sources, for the further advancement of this subfield. Quantitative conservation geography can help inform the implementation of national and international conservation actions and policy to help stem the global biodiversity crisis.

Highlights

We propose quantitative conservation geography, as a subfield of conservation science.

Quantitative conservation geography studies where, when, and what conservation actions could be implemented in order to mitigate biodiversity threats and support sustainable people–nature interactions.

We outline relevant methods and data needed in quantitative conservation geography.

We propose that emerging technologies and digital data sources play an important role in further advancing quantitative conservation geography.

Quantitative conservation geography can help identify sustainable and equitable solutions to address the biodiversity crisis.

Human activities and conservation actions

Human activities are eroding biodiversity, causing extinction of species, and loss of ecosystems, and consequently reducing the contributions nature provides to people [1]. Human pressures include land and sea use change, climate change, pollution, unsustainable use of biodiversity, and the introduction of invasive alien species [2]. Robust global conservation policy and practice require understanding the status, trends, and future of the links between people and nature in order to guide conservation actions, such as the creation of protected areas [3] or restoration of habitats [4], to halt and reverse nature's decline. These interactions take place in the broader context of **socioecological systems** (see Glossary) [5] where both positive and negative outcomes for people and nature can emerge from the ways people shape natural systems [6], and the ways they are affected by nature in return [7]. In the context of such systems, conservation actions have the potential to deliver positive outcomes for both people and nature if properly and carefully planned [8]. Because people–nature interactions vary widely in space and time, it is important to understand where, when, and what conservation actions can address threats and support sustainable people–nature interactions [9].

Geography provides the foundations to explore conservation actions at relevant temporal and spatial scales, from global to local and their interplay, and within the socioecological contexts in which conservation actions take place [10]. There is an important and growing body of literature on conservation, which draws from qualitative geographical tradition [11], including studies in political, critical and feminist human geography. Studies that investigate conservation actions in space and time using quantitative geographical approaches are also abundant and increasing [e.g. 12]. We argue that while the contribution of geographers is strong in conservation science, and conservation is inherently spatial, this role of 'geography' is not fully recognized. To fill part of this gap, we propose the recognition of **quantitative conservation geography**, as a subfield at the overlap between conservation science and geography that studies where, when, and what conservation actions could be implemented in order to mitigate threats and support sustainable people–nature interactions. Quantitative conservation geography combines aspects of human geography (i.e., people and their communities, cultures, and economies) and physical geography (i.e., the living nature across levels of ecological organization encompassing genetic diversity,

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species, and ecosystems). Quantitative conservation geography is different from, but complements the existing subfield of **conservation biogeography**, which is 'concerned with the distributional dynamics of taxa individually and collectively to problems concerning the conservation of biodiversity' [13], in that it also addresses the human dimensions of conservation actions. In the following sections, we discuss the main themes, approaches, and challenges associated with quantitative conservation geography research.

Planning conservation actions: where, when, and what

Existing standard classification systems of threats and conservation actions provide a basis for quantitative conservation geography research [14]. Traditional approaches use information on the spatial distribution, exposure, intensity, and timing of threats [15], in combination with information on the spatial distribution of biodiversity, to identify where and when different conservation actions are necessary. For example, studies have identified areas where conservation actions should be implemented to stop specific causes of ecosystem conversion, such as agriculture [16], urbanization [17], extractive industries [18], and roads and other transportation corridors [19]. Some of these analyses can also incorporate models of projected land use change [20]. Increasingly, studies are also mapping important areas for reducing the vulnerability of biodiversity to climate change [21,22]. Studies have also identified regions for implementation of conservation actions to address unsustainable harvesting [23], invasive species [24,25], and pollution [26].

More proactive approaches can also incorporate information on the spatial distribution of opportunities and constraints, in addition to information on threats and biodiversity, to identify where, when, and importantly what conservation actions should be implemented to help achieve sustainable people–nature interactions. Such approaches require mapping social, economic, political, institutional, and/or cultural factors, which enable or otherwise add to the occurrence or persistence of direct threats. In their simplest form, these approaches require mapping costs, feasibility, and benefits [12]. More advanced approaches, which are often only possible at a regional to local scale, require mapping the values, views, and preferences of multiple stakeholders in the socioecological context under study [27].

Combining multiple data sources

Here, we introduce some of the key data sources, including actionable biodiversity and conservation knowledge products [28], threat, and socioeconomic data, which in our view are important for quantitative conservation geography. Available biodiversity and conservation knowledge products include data on where threatened species occur, what is threatening them and where they are protected [29]. The International Union for Conservation of Nature (IUCN) Red List [30], for example, uses quantitative categories and criteria, to allow transparency, consistency, and repeatability to provide an assessment of species extinction risk [31]. The IUCN Red List has now been implemented to assess the extinction risk of 134 425 species, finding 37 480 to be threatened with a high risk of extinction [32]. More than 82% of these (>111 000 species) have spatial data available. The IUCN Red List also includes information on threats for all species that have been assessed [2,14]. The IUCN Red List of Ecosystems has now been established to assess the risk of ecosystem collapse [33]. International frameworks to assess long-term, cumulative, anthropogenic impacts on biodiversity [34] and the impacts of conservation actions [35] are also under development and can be used to generate data for quantitative conservation geography analyses.

Threats are often difficult to map and thus surrogates, such as accessibility and land use change maps, are often used in place [23,36]. A current limitation, especially at the global level, is the lack

Glossary

Citizen science: the collection and analysis of biodiversity data by members of the public, often as part of a project coordinated by scientists.

Conservation biogeography: the study of distributional dynamics of taxa individually and collectively to inform the conservation of biodiversity.

Conservation culturomics: the study of people–nature interactions through the analysis of digital data.

Quantitative conservation geography: the study of where, when, and what conservation actions could be implemented in order to mitigate threats and support sustainable people–nature interactions.

Scenario analysis: process of analyzing representations of possible futures for one or more components of a system, namely drivers of change in nature and nature's benefits, including alternative policy or management options.

Spatial conservation planning: the use of quantitative methods to guide resource allocation in an efficient manner towards priority areas for conservation actions.

Socioecological systems: complex adaptive systems where social and biophysical agents interact at multiple temporal and spatial scales.

Telecoupling: combined socioeconomic and environmental interactions or flows between two or more socioecological systems that are separated in space.

of threat data with spatial resolution, accuracy, timeliness, repeatability, and accessibility necessary to inform conservation decision-making [37]. Aggregate maps of human impacts on land [38], freshwater [39], and the ocean [40] are available, but they mask the variation in impact of their constituent drivers, making it challenging to identify what conservation actions are best suited to tackle specific threats. Threat maps also often fail to consider how biodiversity responds to conservation actions that mitigate threats in order to guide conservation actions towards where and when they can have the greatest positive impact on biodiversity conservation [15].

Besides threats, quantitative conservation geography also needs information about where and when conservation actions can be implemented without negatively affecting people. Such information is often neither readily available nor easy to map (especially at a global scale), and/or time consuming to collect. Mapping the economic costs and benefits of conservation actions can help identify important areas for conservation actions where limited resources should be invested [41,42]. Mapping people's values, views, and preferences can help identify where local people benefit or are affected by nature, allowing them to have an active voice in planning and implementing conservation actions. Data gathered through surveys, for example, have been used to develop and apply a spatially explicit sociocultural index to inform conservation actions about public values toward wildlife [43]. Indigenous Peoples manage or have tenure rights over a quarter of global terrestrial land that intersects about 40% of all terrestrial protected areas and ecologically intact landscapes [44]. Failure to map their values, views and preferences can result in identifying inadequate conservation actions.

Key methods

Here we introduce some of the key methods that, in our view, are foundational for quantitative conservation geography. Specifically, we focus on approaches that use data introduced above and can be used to identify the conservation actions that should be implemented.

Analyses of telecoupling

In recent years, it has become clear that many of humanity's impacts on biodiversity are telecoupled – that is, the point of impact is distant, often internationally, from the driver. Two methods – environmentally extended input–output analysis and life cycle assessment – both originating in industrial ecology, are becoming increasingly important in understanding telecoupled impacts [45] and have great potential in quantitative conservation geography. Input–output analysis considers the flow of money along each supply chain [46]. Environmentally extended input–output analysis then connects this flow to environmental impacts at each step, for example, for biodiversity, where ~30% of species threats across the IUCN Red List were found to be due to international trade [47]. By contrast, life cycle assessment considers the pressures caused by the production and consumption of specific products [48], but recent innovations have extended this to impacts on species [49] and ecosystems [45]. Hybrid approaches have begun to emerge, combining the benefits of the two methods, for example, to assess embodied impacts of consumption of soy from the Brazilian Cerrado [45] and to map the spatiotemporal changes in global deforestation footprints [50].

Spatial conservation planning

Spatial conservation planning uses quantitative methods to guide resource allocation in an efficient manner towards priority areas for conservation action [12]. Spatial conservation planning aims to identify areas of high biodiversity value for conservation action, or areas of lesser importance to allow for planning of other land uses. Spatial conservation planning can be carried out at multiple scales, from global to local, using ecological, social, economic, and political data. Global analyses have helped identify priority areas for the expansion of the global protected area network to help meet Aichi target 11 (Figure 1) [20,51] and national to local analyses are being used to inform biodiversity conservation and other sustainability policies (Box 1). Many spatial conservation planning analyses have accounted for economic costs to help achieve conservation solutions that meet biodiversity targets under budgetary constraints. Studies that incorporate economic costs in spatial conservation planning, for example, show that an equal or greater level of biodiversity representation can sometimes be achieved with fewer resources when economic costs are included in the analysis [52]. Similarly, win–win opportunities for biodiversity and people can be unveiled when the benefits of biodiversity and ecosystem services are included in conservation planning [41]. However, such analyses generally assume that people are interested in an optimal solution and pursue these solutions rationally. While this assumption is a reasonable first approximation within global analyses, especially in the context of efficient allocation of resources, at finer scales there is a need to better account for social and institutional factors that affect the success of conservation actions. The integration of additional information generated via socioecological research can help address this gap [53]. Public participation geographic information systems can be used to examine the spatial concurrence of a range of spatially explicit social values and land-use preferences and this information can then be included together with ecological data in spatial conservation planning [54]. Spatial conservation planning assessments should also be included into broader land-use planning, as this allows addressing multiple sustainability challenges (e.g., biodiversity loss, climate change, food security) together [8]. Multiple spatial conservation planning tools, including Marxan [55] and Zonation [56], are available.

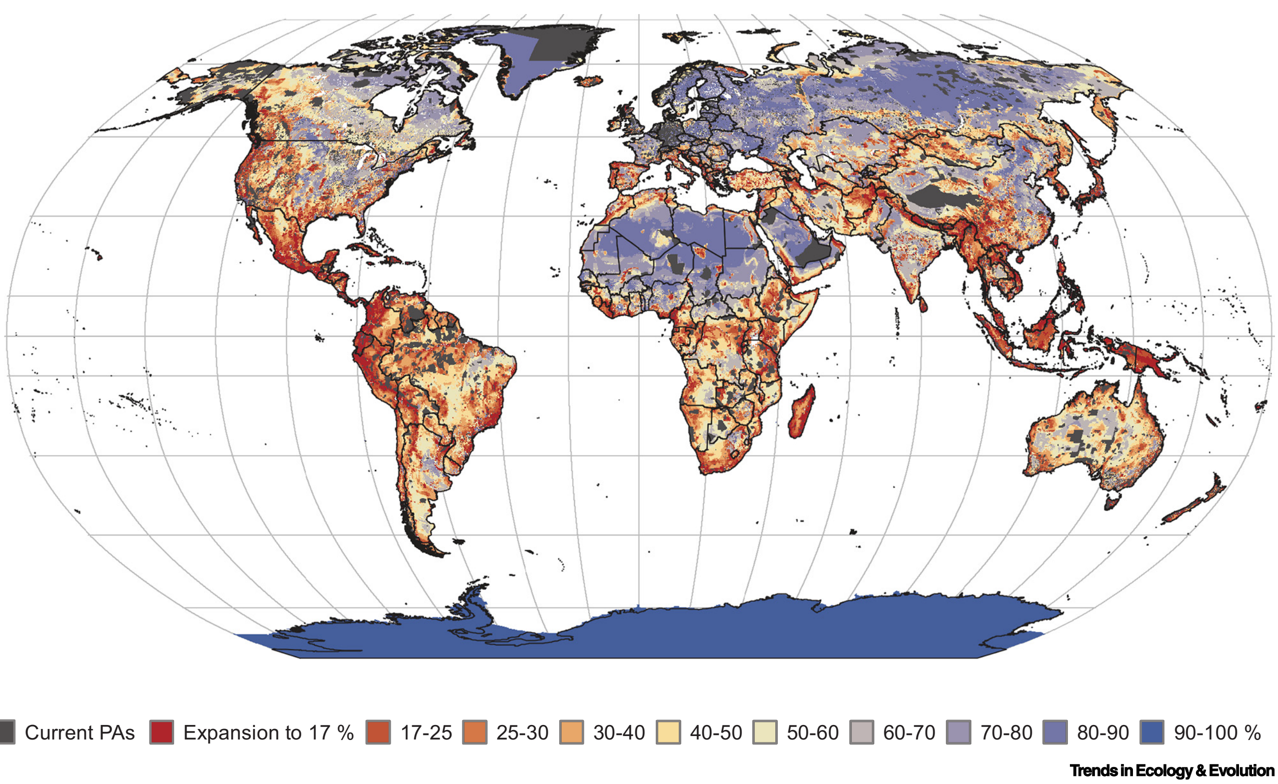

Figure 1. Priority areas for the expansion of the global protected area network, taking future (2040) projected land-use change into account, to help meet Aichi target 11 (i.e., conserving 17% of all terrestrial land and inland water). The analysis combined species range maps from the International Union for the Conservation of Nature Red List and protected areas from the World Database on Protected Areas. Adapted from [20].

Scenarios and models

Scenarios and models can be used to assess the projected outcomes of conservation actions in space and time [57]. Models can be qualitative or quantitative descriptions of people–nature interactions, while scenario analysis provides a tool to investigate how biodiversity might respond to different pathways of future human activities and conservation actions [57,58]. **Scenario analysis** is particularly important for assessing which human activities may lead to unsustainable outcomes for biodiversity and which conservation actions can best counteract them [59,60]. It can also be applied retrospectively to understand likely outcomes in the absence of action, and thus conservation impacts [61]. Most scenarios investigate the impact of human activities on biodiversity, but have not accounted for the role of biodiversity in enhancing human well-being [57]. Integrated assessment models combine information on human activities and scenarios of future development to make projections about the future of biodiversity and people [58]. It remains crucial for future research to better assess and integrate potential synergies and trade-offs between biodiversity conservation and other sustainable development goals, as well as address feedbacks between nature, nature's contributions to people, and human well-being [57]. For this, future research should consider the use of participatory approaches that integrate multiple stakeholders across sectors, the inclusion of indigenous and traditional knowledge, and the development of national to local scenarios that are linked to global scale scenarios and address needs of policy-makers [62].

Filling information gaps

The dynamic nature of socioecological systems demands continued efforts to generate updated knowledge products [63], ensuring the underlying data needed in quantitative conservation geography are relevant and up to date [64]. In the case of biodiversity, **citizen science** platforms, such as iNaturalist (https://www.inaturalist.org/) or eBird (https://ebird.org/home), have amassed millions of locality records. Using citizen science data could help generate more accurate species

Box 1. Spatial conservation planning at the national scale

Spatial conservation planning analyses at the national scale are important, as countries are the main actors in charge of the implementation of conservation policies. Furthermore, national to regional conservation planning assessments can include detailed information about social, economic, and political factors affecting on-the-ground implementation that may not be readily available at global and continental level. Such information is essential to the successful planning and implementation of conservation actions, including the establishment of new protected areas. For example, as a signatory of the Convention of Biological Diversity, Uruguay needed to identify priority areas for the expansion of Uruguay's presently very limited protected area network (<1% of Uruguay was protected) to help reach Aichi target 11. Conservation authorities also aimed to include the strategy for protected area expansion within a broader land-use planning strategy to meet other sustainable development objectives.

Di Minin *et al*. [88] used the spatial conservation planning software Zonation to maximize the representation of biodiversity features and ecosystem services, while exploring the trade-offs with agricultural and commercial forestry production and land cost (Figure I). Specifically, they explored four policy scenarios, ranging from a business as usual scenario where only biodiversity and ecosystem services were included in the analysis to a potentially unsustainable scenario where expansion of alternative land uses and economic development would be given higher priority over biodiversity and ecosystem services. They used information on the spatial distributions of biodiversity, ecosystem services, alternative land uses, and economic data, to identify the most important landowners to engage in the implementation of conservation actions in Uruguay.

At the 17% land target proposed for conservation, the representation levels for biodiversity and ecosystem services were, on average, higher under the business as usual scenario than they were when alternative land uses and land cost were included in the analysis. However, they found that a small addition to the proposed conservation target (17–20% of terrestrial land) would allow to meet same representation levels for biodiversity and ecosystem services, while decreasing conflict with agricultural and commercial forestry production and opportunity costs to landowners. Overall, the results highlighted that more realistic and potentially higher conservation targets, than politically set targets, can be achieved at the country level when sustainable development needs are also accounted for. Surveys with some of the identified landowners are now being used to identify what conservation actions should best be implemented in the identified priority areas in order to avoid conflicts [89]. Data gathered through these surveys can potentially be used to further refine the earlier conservation planning assessment by mapping, for example, landowners' willingness and capacity to participate in conservation actions.

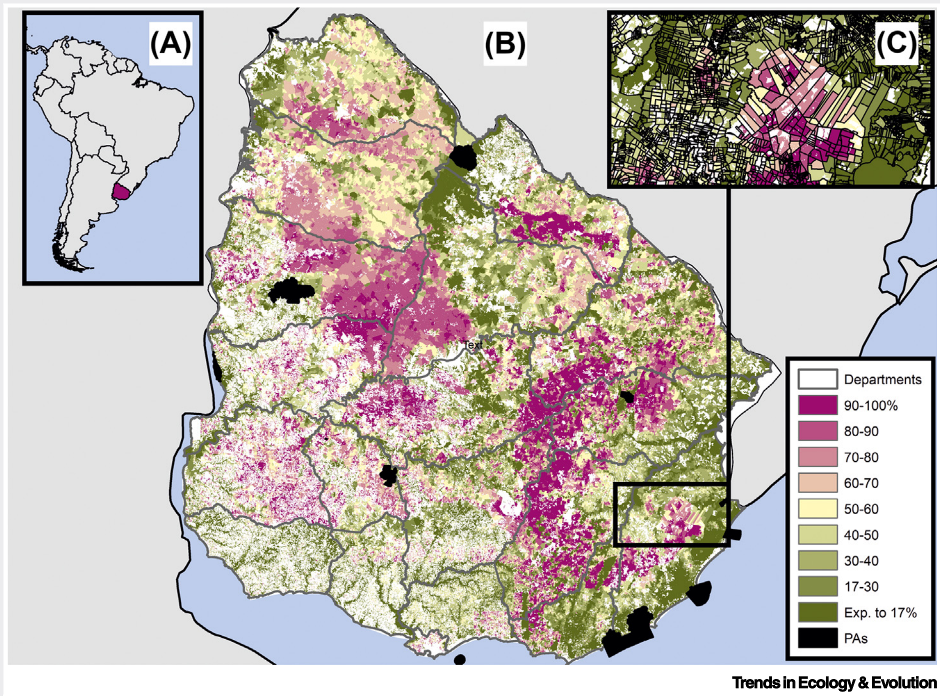

Figure I. Priority rank map for the conservation of biodiversity and ecosystem services in Uruguay obtained by including biodiversity, ecosystem services, alternative land uses and land cost. (A) location of Uruguay (B) the areas identified for the expansion of the protected area network to meet the 17% land protection target (dark green); and (C) how the prioritization used cadastral units as planning units. Departments represent local administrative boundaries within Uruguay. Areas in white are transformed (e.g., intensive agriculture). Adapted from [88]. Abbreviations: PAs, existing protected areas.

range maps and consequently help reduce uncertainty when identifying priority areas for conservation actions [65]. Citizen science data can also be used in **telecoupling** research to better understand large-scale people–nature interactions [66]. There is great potential to harness the same data to strengthen assessment of the impacts of human activities in space and time. In this context, obtaining volunteered geographic information from citizen science can represent an important tool to engage multiple stakeholders (e.g., citizen scientists and experts) in monitoring threats [67]. However, there is an as-yet-vacant niche for established global citizen science platforms to improve documentation of threats (e.g., unsustainable use) to biodiversity, and of conservation responses. Furthermore, citizen social science [68] approaches offer new opportunities to account for social processes when investigating where, when, and what conservation actions should be implemented to support sustainable people–nature interactions through, for example, participation and mutual learning between stakeholders [69]. Public participation geographic information systems and citizen social science can provide an important means of collecting spatially explicit social data (e.g., about the values people associate with biodiversity, places and land-use preferences, therefore indicating their support or conflict over where conservation actions should be implemented).

Emerging technologies provide one promising way forward to minimize an important data gap in relation to biodiversity and threats [70]. Remote sensing has a long history of use in conservation research and can provide valuable data for quantitative conservation geography research. For example, Google Earth Engine was used to create the first-ever global high-resolution map of forests allowing for near-real-time tracking of illegal deforestation [71]. Increasing access to unmanned aerial vehicles (UAVs or drones), however, provides a cheaper and timely alternative to satellite remote sensing, complementing our ability to monitor land use or climate changes at

Box 2. Innovative solutions using digital data and automated content analysis

Social media geotags, as well as text, image, and video content, have already been used in spatial analysis of people–nature interactions [78]. Hausmann *et al*. [80] collected social media data from Flickr and Twitter geolocated in Important Bird and Biodiversity Areas and assessed threats from tourists' visitation and to harness the potential benefits of tourism for conservation. Specifically, social media data was combined with information from the IUCN Red List to map threats and benefits from human visitation in sites of global conservation importance. Continuously accumulating social media data can help reveal temporal patterns and long-term trends in people–nature interactions [90]. Other digital data sources that can be potentially georeferenced, and thus deployed in quantitative conservation geography, include webpages, books, e-commerce platforms, online media and digital encyclopedias [77].

Because of the deluge of data potentially available from digital platforms, automated content analysis is required to cost-efficiently filter and analyze this information (Figure I) [78,91]. Applying computer vision and natural language processing techniques to data from digital platforms can help map the use of natural areas [82] or threats from wildlife trade [91,92]. These novel data sources can potentially be combined with spatial data from the IUCN Red List and telecoupling methods to assess interconnections between demand and supply countries in the supply chain of the wildlife trade. Similarly, information on threats potentially gathered from digital media can help inform biodiversity risk assessments as part of the IUCN Red List and thus inform conservation policy. Social media data can also be leveraged to map opportunities for conservation, for example to assess people's reactions and sentiment for conservation actions [93] and/or threats to both biodiversity and people (e.g., mining). Finally, social media data could potentially be deployed to study socio-ecological systems too (e.g., social network analyses to link multiple stakeholders across space and time).

Figure I. Automated analysis of people–nature interactions from geolocated images obtained from social media platforms using dense captioning that identifies areas of interest in the images and creates a linguistic description for each area. Adapted from [78]. Picture by Tuuli Toivonen in Pallas-Ylläs National Park, Finland.

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relevant temporal and spatial scales. UAVs can be used for example to enhance law enforcement in protected areas [72]. Big-data approaches are also expanding into the aquatic realm [73]; for example, by combining satellite-tracked movements of species and human pressure assessed from global fishing fleets [36], to carry out near-real-time global spatial risk assessments.

The global spread of the internet has also spurred the emergence of new research approaches aiming to take advantage of data hosted in multiple digital platforms [74–76]. One such area is **conservation culturomics**, which focuses on exploring people–nature interactions using a variety of digital data sources [75,77,78]. Among these digital data sources, social media are a particularly relevant data source [79] because their content is often associated with detailed spatial and temporal metadata [78] (Box 2), potentially allowing for real-time monitoring of human activities in areas important for the conservation of biodiversity [80]. Information about people–nature interactions in socioecological systems can be extracted efficiently from text,

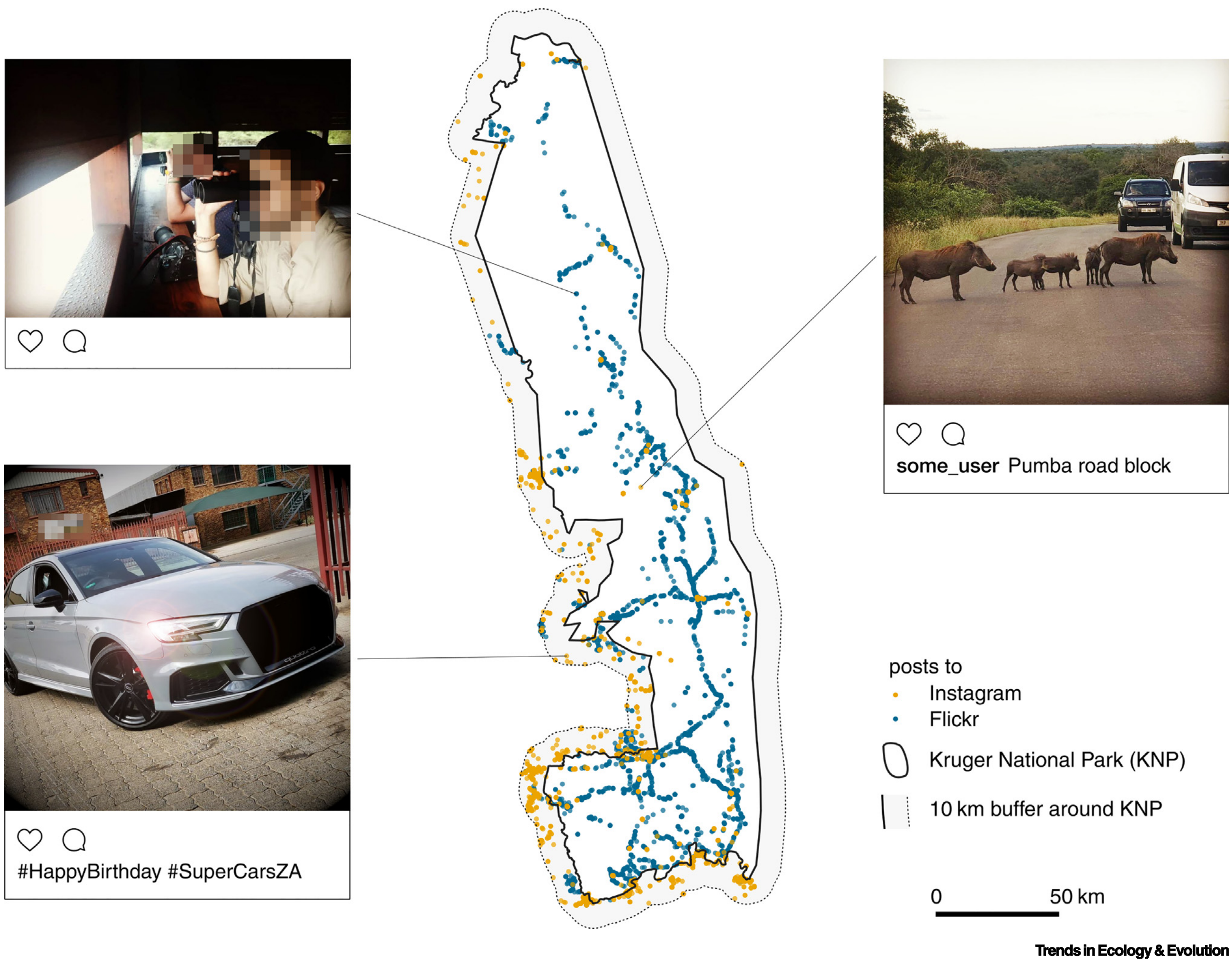

Figure 2. Flickr and Instagram data from the Greater Kruger area in Southern Africa. An important aspect of social media data is that it contains information about the spatial and temporal distribution of biodiversity, their interactions with people, but also information (e.g., the car in the picture) that, while geolocated within a socioecological system, is not relevant for analyses in quantitative conservation geography. To filter this deluge of data and retain only relevant information, automated content analysis, using machine learning and natural language processing, is needed. Social media data available for 2015 were collected from Instagram's (www.instagram.com/developer) and Flickr's (www.fickr.com/api) application programming interface.

images and video using automated content analysis [78,81,82] (Figure 2). Images and text collected from digital platforms could be, for example, used to assess the views, values, and preferences of multiple stakeholders [83].

As a note of caution, emerging technologies and conservation culturomics approaches should be used in full respect of human rights and carefully consider ethical guidelines and data privacy and protection concerns [79,84].

Way forward for quantitative conservation geography

We believe quantitative conservation geography provides a useful framework for quantitative research exploring conservation action in socioecological systems and captures growing research interest in this topic. A search in Web of Science's Core Collection for scientific literature at the intersection between conservation science and geography, followed by automated content analysis [85] of the abstracts of 17 899 studies, allowed the identification of a topic in this literature that addresses the human dimensions of conservation (see Table S1 in supplemental information online). Within this diverse topic, many studies focus on threats, opportunities, and conservation actions in space and time, fitting well with the scope of quantitative conservation geography proposed here. While this suggests there is indeed a growing body of research within the scope of quantitative conservation geography, a systematic review of this literature and further discussion will help refine the scope and implementation of this subfield.

In the future, we call for a broader use of 'conservation geography' to cover 'geographies of' and 'geographies for' conservation [11]. We foresee broader conservation geography research benefiting from combining qualitative and quantitative methods and bridging between scholarly traditions. From the perspective of quantitative conservation geography this could be achieved e.g. through the increased use of mixed methods approaches [86]. For example, qualitative interview data were integrated with quantitative land use change models to develop future scenarios of agricultural expansion in order to inform traditional land production while avoiding deforestation and land degradation in Indonesia [87]. Further advancements in this direction would help position quantitative conservation geography as a research field that promotes better integration between conservation science, geography, and sustainability science.

Furthermore, quantitative conservation geography can contribute to the development of a global digital platform to assess, monitor, and forecast the status of socioecological systems by integrating biodiversity (e.g., the IUCN Red List, the World Database of Protected areas, etc.), threat (e.g., plans for infrastructure development, satellite images of deforestation, etc.), and social (e.g., public participation geographic information system data, spatial maps incorporating traditional knowledge, etc.) data at multiple scales. Ideally, this platform would allow the integration of traditional and novel data sources and methods. It could also support the engagement of multiple stakeholders across sectors and inclusion of indigenous and traditional knowledge to inform decision-making.

Concluding remarks

We propose that quantitative conservation geography can be used to identify sustainable and equitable conservation actions to address the global biodiversity crisis and other sustainability challenges (see Outstanding questions). This new research subfield is well positioned to inform the implementation of national and international conservation agreements, including the emerging post-2020 Global Biodiversity Framework, as well as the 2030 Agenda for Sustainable Development overall.

Outstanding questions

How can we develop enhanced models on the distribution of threats, opportunities, and conservation actions to inform conservation decision-making?

How to better integrate multiple stakeholders and include indigenous and traditional knowledge and other social data in the development of national to local scenarios that are linked to global scale scenarios?

How can emerging technologies and digital platforms be leveraged to assess, monitor, and forecast the status of socioecological systems by integrating biodiversity, threat, and social data at multiple scales?

How can mix-method approaches be used to combine qualitative and quantitative methods and data from multiple sources to understand what conservation actions are most adequate at relevant temporal and spatial scales?

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Declaration of interests

No interests are declared.

Supplemental Information

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