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Remotely sensed effectiveness assessments of protected areas lack a common framework: A review

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Abstract
Effective protected areas reflect socio-ecological values, such as biodiversity and habitat maintenance, as well as human well-being. These values, which safeguard ecosystem services in protected areas, are treated as models for the sustainable preservation and use of resources. While there is much research on the effectiveness of protected areas in a variety of disciplines, the question is whether there is a common framework that uses remote sensing methods. We conducted a qualitative and a quantitative analysis of 44 peer-reviewed scientific papers utilizing remote sensing data in order to examine the effectiveness of protected areas. Very few studies to date have a wide or even a global geographical focus; instead, most quantify the effectiveness of protected areas by focusing on local-scale case studies and single indicators such as forest cover change. Methods that help integrate spatial selection approaches, to compare a protected area's characteristics with its surroundings, are increasingly being used. Based on this review, we argue for a multi-indicator-based framework on protected area effectiveness, including the development of a consistent set of socio-ecological indicators for a global analysis. In turn, this will allow for globally applicable use, including a concrete evaluation that considers the diversity of regional parameters, biome-specific variables, and political frameworks. Ideally, such a framework will enhance the monitoring and evaluation of global strategies and conventions.

KEYWORDS
effectiveness, protected areas, remote sensing, socio-ecological indicators

INTRODUCTION

Protected areas are global measures applied to protect and sustain biodiversity, as well as to find ways in which human–nature interactions coincide for mutually beneficial outcomes (UNEP-WCMC, IUCN, and NSG, 2020). There is a growing consensus that—in terms of globally increasing human pressure—protected areas enable to a certain extent the short- to midterm conservation of species and natural ecosystems (Chape et al., 2005; Gaston et al., 2008; Geldmann et al., 2019; Ibisch et al., 2016; Joppa & Pfaff, 2011; Mora & Sale, 2011). The development of protected areas is a key approach in the implementation of global agendas for conservation and sustainable development, such as the Aichi targets set by the Convention of Biological Diversity (CBD), the United Nations' Sustainable Development Goals, and national and supranational (e.g., EU-wide) biodiversity strategies. However, most strategies focus on coverage of protected areas as single indicators for the effective protection of biodiversity (Beresford et al., 2018; Chape et al., 2005; Mora & Sale, 2011). It has already been stressed that maintaining as well as establishing new protected areas on a global scale will not be sufficient to sustain biodiversity in the long term (Mora & Sale, 2011). Even after decades of addressing the challenge of establishing and managing protected areas that are fit for purpose, there is sparse information on their effectiveness regarding quantitative outcomes related to biodiversity conservation and ensuring the ongoing functioning of ecosystems (Ghoddousi et al., 2021). The recently published multidimensional framework to assess the socio-ecological effectiveness of protected areas suggests to measure ecological and social outcomes as well as socio-ecological interactions and indicates remote sensing as one promising method to advance these assessments (Ghoddousi et al., 2021). Quantifying effectiveness is crucial when seeking to provide evidence as to whether the designation of protected areas enables positive changes regarding ecosystem services, biodiversity conservation, an increase in resilience, and other factors (e.g., Chape et al., 2005; dos Santos Ribas et al., 2020; Nagendra et al., 2013). Otherwise, there is the risk that the creation of increasingly more protected areas will encourage displacement behavior and obstruct our view of the key question, namely, safeguarding the global ecosystem (Adams et al., 2019; Watson et al., 2014).

The effectiveness approach, based on remote sensing, attempts to measure to what extent protected areas really safeguard biodiversity and measure their ecosystem functions. Studies on the ecological functioning of protected areas, as well as on measures of management effectiveness, are widely available, and yet, studies on global management effectiveness especially highlight a lack of information that integrates conservation and management efficacy objectives (Leverington et al., 2010). In conservation studies, socio-ecological features are extensively used to identify the effective protection of certain areas (Ghoddousi et al., 2021). Building on a socio-ecological perspective, our understanding of protected area effectiveness is based on three factors: (1) mitigating biodiversity and habitat loss, (2) providing ecosystem services for human well-being, and (3) having a sustainable impact on the surroundings of the protected area by being a flagship region. Within our approach, sustaining biodiversity with the help of protected areas is our effectiveness measure, and it is delimited by efficiently managing protected areas.

Protected areas have been investigated from different viewpoints. The global standard employed to categorize protected areas according to their use restrictions has been the basis for different studies and was initially developed by the International Union for Conservation of Nature (IUCN) (World Conservation Union) (Dudley et al., 2013). These IUCN protection categories have been examined on a global scale in terms of effectiveness in halting forest cover loss (Leberger et al., 2020), and they have also been tested for biodiversity variables (Gray et al., 2016). This study, for example, found higher levels of biodiversity inside terrestrial protected areas than outside (Gray et al., 2016). These categories have been included in a proposal to assess conservational effectiveness, in order to "ensure a global approach to assessment, measure biodiversity conservation effectiveness, and incorporate new data layers and more effective application of IUCN protected area management categories" (Chape et al., 2005). A global study on habitat cover and species population revealed limited evidence of how protected areas benefit flora and fauna (Geldmann et al., 2013), while human pressure on protected areas is increasing across the world (Geldmann et al., 2019). However, encouraging results on multipurpose protected areas have been presented, illustrating that they can benefit biodiversity by integrating the protection of species' habitats with sustainable land use while simultaneously reducing CO_2 emissions (Nelson & Chomitz, 2011). In addition to the establishment of protected areas, the conservation of areas with low levels of anthropogenic disturbance, such as roadless areas, is another measure utilized to preserve biodiversity at all levels and to protect relevant ecosystem services (Ibisch et al., 2016). The delivery of ecosystem services has become a major objective for those seeking to study and enhance the effectiveness of protected areas (Friedlander et al., 2007), showcasing the harmonization of values people perceive from nature. However, (spatial) data on protected areas, especially regarding habitat coverage and geopolitical features, are still in short supply (Chape et al., 2005; Gaston et al., 2008), thereby resulting in clear conservation gaps and a lack of priority setting (Chape et al., 2005).

Since the turn of the century, the paradigm of protected area effectiveness has shifted from studies solely focusing on the conservation of biodiversity toward an increasing integration of human well-being (Nagendra et al., 2010; Naughton-Treves et al., 2005; Nelson & Chomitz, 2011). Protected areas should be perceived more as functional, intact ecosystems on a regional scale rather than areas with strict use constraints and hard borders (Knorn et al., 2012; Moreno et al., 2019). This would encourage critics who warn against isolating protected areas too much from one another and who instead advocate for integrated protected landscapes (DeFries et al., 2010; Southworth et al., 2004)—exemplified in the land-sharing/land-sparing debate (Fischer et al., 2014; von Wehrden et al., 2014).

Remote sensing is a tool widely used to assess the condition of protected areas. It is considered an effective, comparatively inexpensive instrument and is less time-consuming than evaluation by ground-truthing, and it can also be used globally (e.g., Tuholske et al., 2017). In protected area research, remote sensing—among other approaches—can be used to identify potential protected areas (Goodell et al., 2018) or to study the connectivity between protected areas (Crochelet et al., 2016). Herein, we investigated remote sensing studies to review how effectiveness is measured on a large scale, and which indicators are suitable for the remote sensing analysis of protected area effectiveness. We focused particularly on how remote sensing is used to assess the socio-ecological effectiveness of protected areas.

The aim of this review paper is to analyze the existing body of scientific literature utilizing remote sensing to investigate the effectiveness of protected areas. The depth of understanding and the use of effectiveness concepts are parts of this investigation. In addition, we examine which indicators are used to assess the socio-ecological effectiveness of protected areas, and we present a first classification of spatial selection methods for remotely sensed effectiveness indicators.

METHODS

In order to identify existing literature on methods used to assess the effectiveness of protected areas, we brought three research areas together: research utilizing remote sensing, the framework of effectiveness, and protected areas as target areas. To cover a wide range of approaches, we foresaw from including specific terms on socio- and/or ecological effectiveness. We rephrased the approach for all databases on the Web of Science search engine by using the following search string: ("remote sensing "OR "satellite imagery "OR geodata OR geoinformation OR geospatial) AND (effectiveness OR impact* OR efficiency) AND ("biosphere reserve* "OR "protec* area*").

The dataset created via Web of Science on 12 February 2020 revealed a list of 520 published academic papers. Of the 520 identified studies, we first selected 285 based on the abstract. We screened the abstracts for relevance and determined if the study was an empirical investigation using any kind of geoinformation to analyze the effectiveness of and/or impacts on protected areas. After examining the full text of the 285 remaining articles, we excluded a further 241 papers, as they did not include any perception of effectiveness, did not include a comparison approach with adjacent areas, or focused on management effectiveness solely. A final set of 44 relevant papers, written in English and Spanish, remained and was downloaded for our evaluation (Appendix S1). They were then read by one reviewer in detail, and relevant variables were extracted (Table 1).

We counted the number of indicators used to assess the effectiveness of protected areas without co-explaining indicators; that is, we did not include co-indicators (e.g., climate change and human impacts) explaining the main indicator (e.g., forest degradation). The types of indicators were categorized into six groups: land use/land cover change (LUCC), forest cover change, vegetation cover change (e.g., vegetation productivity with nonvegetation cover excluded), fire, habitat ecology (animal observations and migration effects), and marine indicators (e.g., species assemblages). The spatial scale was categorized into five categories, and a local scale was assigned if a particularly small area was examined (<5000 km^2). The regional scale included larger areas with either bigger protected areas or various protected areas in one region. Studies were categorized as "continental" when an entire continent was studied. The zonal scale was applied for studies based on global

TABLE 1 Set of variables to categorize paper content and corresponding description

No.	Variable	Description
1	Year	Year of publication
2	Number of indicators	Number of indicators used to assess the effectiveness of protected areas
3	Type of indicators	Type of indicator, research subject
4	Spatial scale	Study scope with 1, local; 2, regional; 3, continental; 4, zonal; 5, global
5	Effectiveness	Study results indicating e (effective protection), i (ineffectiveness timewise or worse inside than outside), and d (divergent, no effect or positive and negative effects)
6	Spatial selection	Area selection approach: Methods used to select areas for comparison inside and outside of the protected area
7	Time scale	Time series analysis or cross-sectional approach
8	Study area	Continent on which the study was conducted
9	Authors origin	Current residence of the main author
10	Ground truth	Yes or no; additional ground truthing as in field research or household surveys

biome borders, that is, temperate forests or the tropics. Additionally, we focused on the design of the studies in terms of the spatial selection of indicators, to assess the effectiveness of protected areas. There is a simple "inside–outside" approach, where specific parameters are compared inside and outside of protected areas (Gray et al., 2016). For example, it can be verified whether a certain type of forest is more affected by the loss of cover outside a protected area than inside—a corresponding outcome would support a certain level of plausibility in terms of protection effectiveness. To ensure the comparability of variables inside and outside of protected areas, a matching methodology (Beresford et al., 2018), whereby data extraction points are sampled randomly inside and outside protected areas with matching similar socio-ecological characteristics (e.g., distance to human settlements or elevation), is becoming more and more prominent in research. A detailed breakdown of applied spatial selection methods is presented in the "Results" section.

One focus of this study was to establish how existing approaches assess effectiveness by comparing protected areas with their surroundings, because the sole assessment of changes over time inside a protected area can provide insights into variabilities inside the area, but it cannot relate to possible changes in surroundings. Against this backdrop, the selected studies, which all use inside–outside comparisons, were categorized in terms of time series analysis or a cross-sectional approach.

RESULTS

The approaches, spatial scales, selected indicators, and declared levels of effectiveness varied widely across the 44 selected studies. Although the Web of Science database covers publications since 1990, the selected studies were all published between 2004 and 2019, with an increase in publications after 2010 and further after 2015, indicating a rather emerging research field. Most of the studies used only a single indicator to assess the effectiveness of protected areas, and the choice of the indicator was independent of the study's spatial scale (Figure 1a). Regarding the spatial scope of the studies, three used area data on global biomes, that is, tropical forests (Lui & Coomes, 2016; Wright et al., 2007) and the temperate biome (Sommerfeld et al., 2018), one of them dealt with the entire African continent (Beresford et al., 2013), and one conducted a global analysis (Tang et al., 2011) (Figure 1a). In the context of scoping, mostly protected area boundaries were used for delineation, some selected national boundaries for regional analyses, and only a few used biome boundaries for global analysis. As for the perception of protected areas' effectiveness, 18 studies stated an improvement in the situation, while a few studies ($n = 7$) detected a certain ineffectiveness. Almost half of the studies ($n = 19$) presented divergent results (Figure 1a).

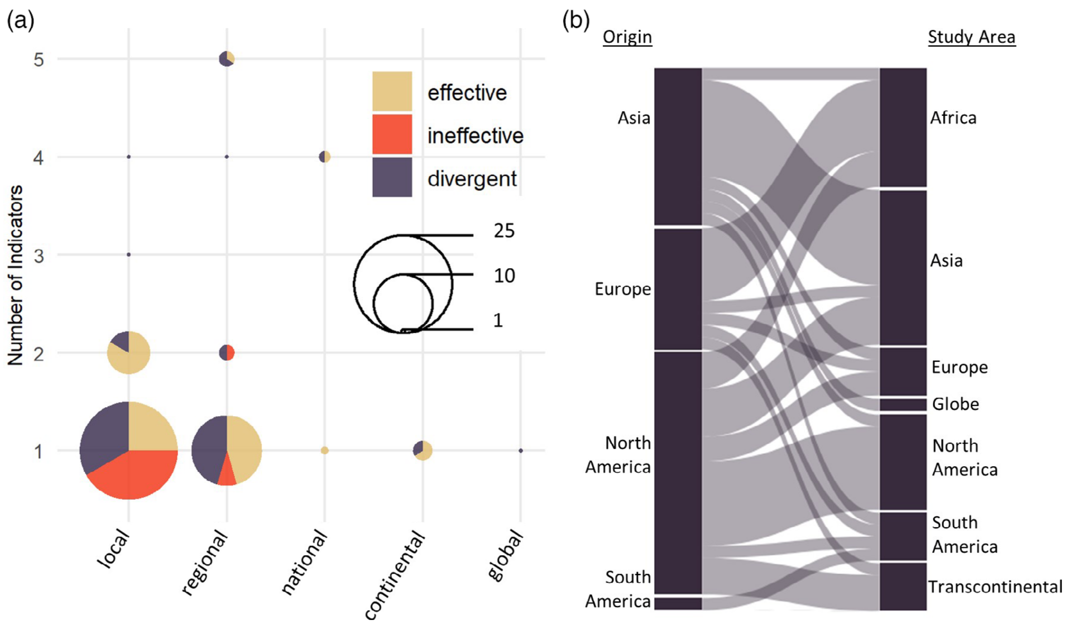

FIGURE 1 (a) An overview of the main characteristics represented across the studies used in this review. The pie chart size represents the number of papers (total $n = 44$). Every pie chart is located according to the study scope (x-axis) and the number of indicators used to assess the effectiveness of protected areas (y-axis). Every pie chart is divided by the number of studies that indicate effective protection (timewise or improvement inside), divergent results (no effect or positive and negative effects), or ineffective protection (timewise or worse inside than outside). (b) The origin of each main author in relation to the examined study area ($n = 44$). The study region "transcontinental" includes studies conducted in the temperate biome, the tropics, and one study conducted in Asia and South America

The majority of studies were conducted on local or regional scales in Asia ($n = 13$), Africa ($n = 10$), North America ($n = 7$), South America ($n = 5$), and Europe ($n = 4$). Studies conducted in Asia and North America were done by indigenous scientists, whereas studies on the African continent were implemented by scientists based in Europe, North America, and Asia (Figure 1b).

Perception and definition of the effectiveness of protected areas

The effectiveness of protected areas was the main focus of studies on rare occasions, and very few studies set out a clear description or definition of how they conceptualized effectiveness (Beresford et al., 2013, 2018; Tang et al., 2011); instead, most of them defined the effectiveness of protected areas as the ability to sustain biodiversity, mostly in terms of selected species (Bonilla-Mejia & Higuera-Mendieta, 2019; Friedlander et al., 2007; Joseph et al., 2009; Kintz et al., 2006; Knorn et al., 2012; Lui & Coomes, 2016; Moreno et al., 2019; Rioja-Nieto et al., 2015; Schulte to Buehne et al., 2017; Xie et al., 2012; Zhang et al., 2017). One of the included papers, Tang et al. (2011), described the effectiveness of protected areas as the ability to "[maintain] ecological functioning" and divided ecological effectiveness into two subfunctions: one part concentrating on existing biodiversity features in protected areas, the other part asking "how well [do] these areas maintain the biodiversity features[?]" (Tang et al., 2011). Beresford et al. (2013), however, defined the effectiveness of protected areas as the ability to "[reduce] deleterious land cover change" and "[prevent] conversion of all habitats in sites of high importance" (Beresford et al., 2013). The follow-up study by Beresford et al. (2018) declared effectiveness in terms of protecting natural habitats, specifically referring to "the degree to which that threat is reduced by designation" (Beresford et al., 2018).

Studies with a main focus on habitat protection assessed the effectiveness of these protected areas among other aims, such as preventing habitat destruction and protecting endangered wildlife (Clerici et al., 2007; Foo & Numata, 2019; Huang et al., 2019; Merkohasanaj et al., 2019; Onojeghuo & Onojeghuo, 2015; Simons-Legaard et al., 2018; Sunderland-Groves et al., 2011; Xie et al., 2012).

Many studies defined protection effectiveness through protecting forest cover (Bonilla-Mejia & Higuera-Mendieta, 2019; Foo & Numata, 2019; Gaveau et al., 2012; Nagendra et al., 2004; Phua et al., 2008; Ren et al., 2015; Wright et al., 2007), or more specifically in terms of protection efficacy by preventing forest fires (Manaswini & Reddy, 2015) or mitigating tree cover loss (Bragina et al., 2015). Others specified the effectiveness of forested protected areas regarding deforestation or even—more specifically—forest degradation (Htun et al., 2009; Southworth et al., 2004).

Overall, 18 studies declared the good effectiveness of their investigated protected areas, always with their individual definition of effectiveness, while seven highlighted the need to improve in this regard. A total of 19 studies presented a mixed picture, highlighting both positive and negative effects. In studies focusing on forest protection, the effective protection of forest cover inside protected areas was identified, but strong pressure on adjacent areas limited any positive effects (Blackman et al., 2015; Clerici et al., 2007; Lui & Coomes, 2016; Nagendra et al., 2009; Xie et al., 2012).

In terms of different approaches on protected area effectiveness, we found that nine of the 44 studies complied with our proposed definition of effectiveness (Figure 2, Group A). In 18 studies, we found two of the three factors (Figure 2, Groups B and C) and 17 studies covered mainly the mitigation of biodiversity loss as definition of protected area effectiveness (Figure 2, Group D). Explicit social aspects (defined as ecosystem services for human well-being) were found in 16 studies (Figure 2, Groups A and C).

Spatial selection of remotely sensed indicators

Different methodological approaches utilized to extract and compare indicators were identified. Twenty-eight studies used either an "inside–outside" or an "inside–outside–buffer" approach (Figures 3a,b). The other main spatial selection approaches used either the protected area as land cover for comparison ($n = 9$; Figure 3c) or a matching method to compare features inside and outside of protected areas ($n = 7$; Figure 3d).

The inside–outside approach (Figure 3a) was mostly just applied in a way that areas inside and outside of protected areas were compared (Bonilla-Mejia & Higuera-Mendieta, 2019; Friedlander et al., 2007; Gaveau et al., 2012; Huang et al., 2019; Leisher et al., 2011; Rioja-Nieto et al., 2015; Sommerfeld et al., 2018), while others compared "outside" areas in the direct periphery of the protected areas (Clerici et al., 2007; Foo & Numata, 2019; Mtui et al., 2017; Nagendra et al., 2009; Sunderland-Groves et al., 2011).

The second large group of studies ($n = 14$; Figure 3b) used an inside–outside–buffer approach, mostly involving separating areas inside and outside of protected areas with a buffer zone in between, to take into account potential edge effects (Fuda et al., 2016; Htun et al., 2009; Lui & Coomes, 2016; Onojeghuo & Onojeghuo, 2015; Phua et al., 2008; Schulte to Buehne et al., 2017; Simons-Legaard et al., 2018; Southworth et al., 2004; Tang et al., 2011; Zhang et al., 2017). Others added continuous buffer zones around

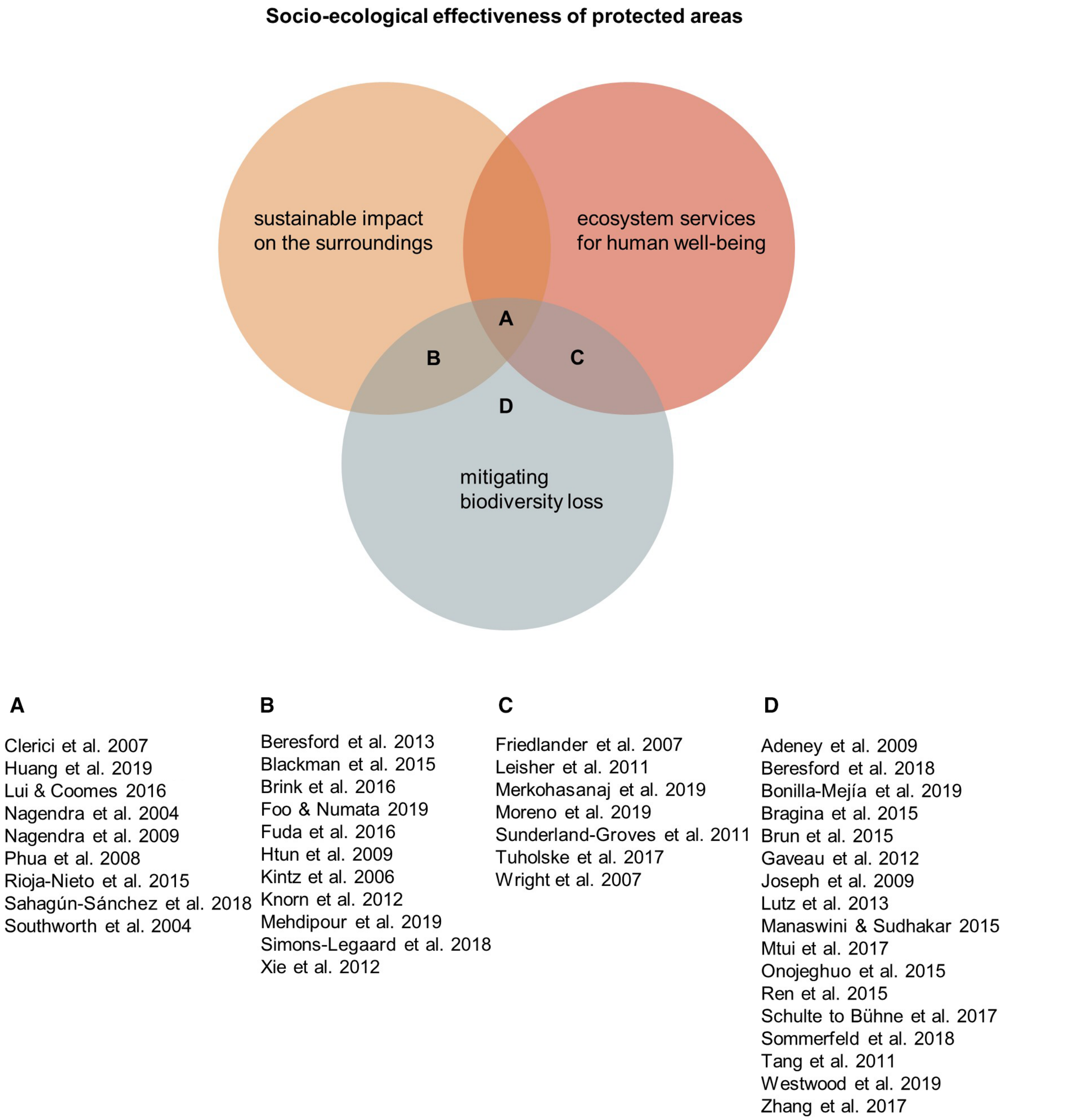

FIGURE 2 Integration of the investigated studies into our perception of socio-ecological effectiveness of protected areas. "A" signifies that the corresponding studies indicated all the factors (mitigating biodiversity loss, ecosystem functions for human well-being, and sustainable impact on the surroundings) in their perception of protected area effectiveness. "B" includes studies that defined effectiveness as mitigating biodiversity loss and having a sustainable impact on the surroundings. "C" lists studies that defined effectiveness as mitigating biodiversity loss and providing ecosystem services for human well-being. "D" includes studies that measured protected area effectiveness investigating the mitigation of biodiversity loss

core zones or the outer border of the protected area (Knorn et al., 2012; Nagendra et al., 2004; Wright et al., 2007). Random sampling integrated into an inside–outside–buffer research framework was noted in two articles (Merkohasanaj et al., 2019; Westwood et al., 2019).

Besides the explicit study of protected areas, several studies defined protected areas as one aspect of land cover and considered whole ecosystems or ecological regimes (Figure 3c). Studies on deforestation (Brun et al., 2015), fire patterns causing deforestation (Adeney et al., 2009; Manaswini & Reddy, 2015), land cover change (Kintz et al., 2006; Mehdipour et al., 2019; Sahagún-Sánchez & Reyes-Hernández, 2018; Tuholske et al., 2017; Xie et al., 2012), and changes in timberline elevation (Lutz et al., 2013) examined whether or not areas under protection suffered less from these threats.

The rather recently proposed matching method (Figures 3d and 4) is complex, and it varies in line with

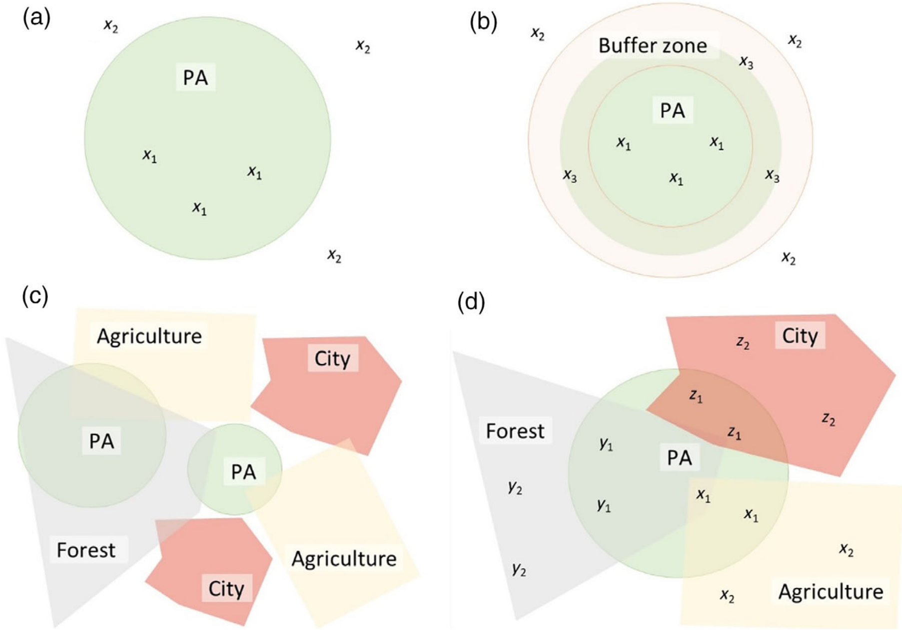

FIGURE 3 Schematic diagram of methodological approaches used to spatially extract and compare indicators, in order to assess the effectiveness of protected areas (PA). (a) Inside–outside; (b) inside–outside and buffer zone; (c) protected area as land cover class; (d) matching indicators inside and outside, based on similar characteristics

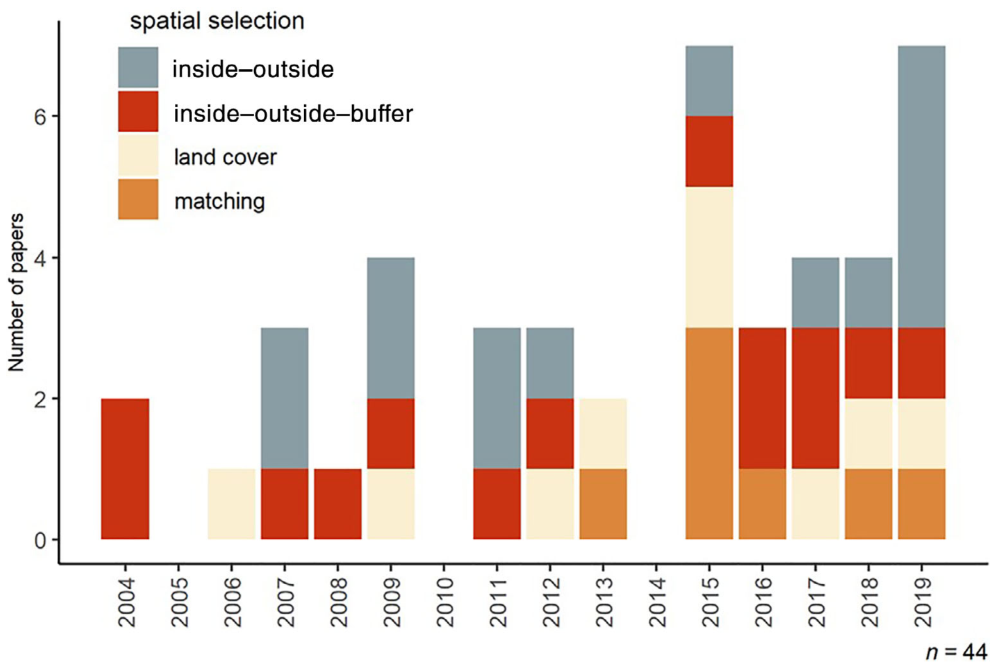

FIGURE 4 The use of different spatial selection methods in selected papers over time. Bar colors indicate the different spatial selection methods for comparing indicators "inside–outside," "inside–outside–buffer" (including a buffer area between the protected area and its surroundings), "land cover" (protected area [PA] as land cover class), and "matching" (random sampling inside and outside *with* similar characteristics)

the focus of the respective study. The selection of similar characteristics to match points inside and outside of protected areas was adapted to the subject of interest: In studies on land cover change, characteristics that might have an impact on land cover change were used to select suitable comparison points (Beresford et al., 2013, 2018).

The same idea, using characteristics possibly influencing the study subject, was used in other studies for habitat types (Brink et al., 2016) and forest canopy cover (Blackman et al., 2015; Bragina et al., 2015; Moreno et al., 2019; Ren et al., 2015).

For the spatial selection of indicators, Landsat derivatives ($n = 18$) were primarily used for remote sensing analysis. MODIS data were analyzed in five studies only, while other studies combined MODIS and Landsat, Landsat and ASTER, or others. Forty-one of the 44 selected studies generated time series for change detection over time. More than half of the studies used any type of inside–outside or inside–outside–buffer approach, followed by a method that defined protected areas through land cover class. The use of the matching approach to select data points randomly occurred first in 2013 in the set of selected articles (Figure 4).

Indicators used to assess the effectiveness of protected areas

Landscape indicators were used in 42 studies, whereas two studies used seascape indicators. The primary focus of the studies was related to LUCC ($n = 23$) analysis, with vegetation or explicit forest cover change ($n = 17$) as the main indicators to assess the effectiveness of protected areas. Additional indicators for the remote sensing on which this review focuses were, for example, avian point count surveys (Westwood et al., 2019), chimpanzee observations (Sunderland-Groves et al., 2011), and household surveys (Leisher et al., 2011).

The overall procedure implemented in studies using LUCC as an indicator of effectiveness involved developing a land use classification via satellite data analysis and the subsequent detection of change over time (Beresford et al., 2013), some with a detailed description of their methods (e.g., Schulte to Buehne et al., 2017). LUCC was used to detect changes to and pressure on wildlife protected areas (Brink et al., 2016; Clerici et al., 2007; Mtui et al., 2017), vegetation cover (Huang et al., 2019), forest cover and forest fragmentation (Nagendra et al., 2009; Rioja-Nieto et al., 2015; Simons-Legaard et al., 2018; Sommerfeld et al., 2018; Southworth et al., 2004), forest leakage (Foo & Numata, 2019; Lui & Coomes, 2016), and landscape fragmentation (Mehdipour et al., 2019; Xie et al., 2012) and to identify loss of natural habitats (Beresford et al., 2018). LUCC was also used to assess the impact of anthropogenic pressure (such as urbanization, agriculture, and tourism) and thereby evaluate the vulnerability and ability of the protected area to reduce pressure on biodiversity (Sahagún-Sánchez & Reyes-Hernández, 2018; Schulte to Buehne et al., 2017; Tuholske et al., 2017; Zhang et al., 2017).

Apart from LUCC, many studies that focused on the effectiveness of forest protected areas used the following indicators: the forest loss/deforestation rate (Bragina et al., 2015; Gaveau et al., 2012; Onojeghuo & Onojeghuo, 2015; Phua et al., 2008; Ren et al., 2015), the disturbance rate (Knorn et al., 2012), both (Htun et al., 2009), fire (Adeney et al., 2009; Manaswini & Reddy, 2015; Wright et al., 2007), or the deforestation rate linked with additional variates (Blackman et al., 2015; Bonilla-Mejia & Higuera-Mendieta, 2019). Indicators such as the normalized difference vegetation index (NDVI) or net primary productivity were used to examine effectiveness (Fuda et al., 2016; Joseph et al., 2009; Leisher et al., 2011; Moreno et al., 2019; Simons-Legaard et al., 2018; Tang et al., 2011). Outstanding approaches used changes over time to the mountainous timberline as an indicator (Lutz et al., 2013) or species distribution models (Sunderland-Groves et al., 2011; Westwood et al., 2019). Indicators for marine protected areas were species habitat distribution models using topographical characteristics and assemblages of animals (Friedlander et al., 2007; Merkohasanaj et al., 2019).

DISCUSSION

Our review identified an increasing research interest in the effectiveness of protected areas from a remote sensing perspective. There is not currently a consistent framework for the effectiveness of protected areas or an explicit indicator system that can be employed to assess socio-ecological effectiveness. Therefore, we recommend two main steps toward establishing such a framework: first, the development of a consistent indicator system that explicitly addresses the socio-ecological effectiveness of protected areas for an evaluation of protection efforts to date and in the future, and second, the further elaboration of the matching method for the spatial selection of indicators for a broad application on local and global scales.

Remotely sensed indicators to assess socio-ecological effectiveness

With regard to commonly used terms, the handling of socio-ecological effectiveness is fitted to specific areas of research without searching for an overarching or a consistent use of terms. There is usually no critical reflection on the fact that a comparison of socio-ecological characteristics inside and outside protected areas is not a consistent measurement being that measured differences are indicators of protection (Tang et al., 2011) or effectiveness. However, there seems to be agreement that safeguarding biodiversity is the main concern of protecting landscapes and seascapes (Knorn et al., 2012; Moreno et al., 2019; Schulte to Buehne et al., 2017; Zhang et al., 2017) (Figure 2). Unfortunately, though, a common definition of the concepts of biodiversity is not available either. Apparently, a couple of studies referred to categories of protection following the IUCN and reached different conclusions regarding the effectiveness of protection strictness. A higher level of protection could prevent more anthropogenic pressure (Schulte to Buehne et al., 2017), and yet, strictly protected areas are not necessarily more protective than less restricted protected areas (Ferraro et al., 2013). Roughly 20% of the investigated studies complied with our proposed definition of socio-ecological effectiveness. The majority (41%) covered two of three factors. We thereby acknowledge that the concepts of socio-ecological effectiveness shift toward more holistic approaches (e.g., Ghoddousi et al., 2021). Although several studies defined protected area effectiveness as being a composite of socio- and ecological factors, only few translated this definition explicitly into a corresponding set of socio-ecological indicators (e.g., Huang et al., 2019; Nagendra et al., 2009). As a result of the investigated diverse range of existing definitions, we propose our introduced understanding of protected area effectiveness as the effectiveness of (1) mitigating biodiversity and habitat loss, (2) providing ecosystem services for human well-being, and (3) having a sustainable impact on the surroundings of the protected area by being a flagship region. Equally, this definition calls for subsequent research to define remotely sensed indicators depicting the socio-ecological effectiveness of protected areas (e.g., Ghoddousi et al., 2021; Pettorelli et al., 2018).

Although there is a significant amount of variety in terms of remotely sensed indicators, there is no systematic framework or harmonization of relevant indicators; most studies focused on one indicator to assess the effectiveness of areas, especially in regard to forested regions. Nevertheless, they still included indicators such as fire and distance to roads, fire, and climate phenomena (Adeney et al., 2009), or logging, transport costs, and protected area status (Brun et al., 2015). With a main focus on biodiversity, most approaches studied features such as species composition, fragmentation rate, or LUCC, while only a few used indirect proxies of ecosystem functioning, such as the NDVI (e.g., Htun et al., 2009; Huang et al., 2019; Tang et al., 2011). Studies using forest cover change as a proxy for protected area effectiveness did not reflect that this proxy cannot be applied for nonforested protected areas and therefore cannot be treated as a general proxy for protected areas effectiveness (Geldmann et al., 2019).

Since only three studies of the selected papers mentioned climate change as an influencing factor and used climate variables as indicators, it should be discussed how—and whether—climate variables should not always and generally be taken into account (Huang et al., 2019; Westwood et al., 2019). In the context of climate change, more holistic approaches that include long-term perspectives and vulnerability to climate change would change the view on the effectiveness of protected areas (Freudenberger et al., 2013; Huang et al., 2019). Another potential indicator could be the effectiveness of protected areas in carbon sequestration (Gaveau et al., 2012) or meso- and microclimatic buffering.

Social aspects of socio-ecological effectiveness

Apart from the general consensus that protected areas are a necessary instrument to counteract the loss of biodiversity and to preserve natural habitats, the issue of environmental justice is neglected in many cases. We consider environmental justice as a key factor in investigating the socio-ecological effectiveness, appropriateness, and long-term success of protected areas. One statement to this effect was made in the literature under consideration: “Often parks are created in areas where poor people depend upon the natural resources for their livelihoods; thus, exclusionary management raises issues of social justice and equity” (Bates & Rudel, 2000; Brockington, 2002, cited in Nagendra et al., 2004).

There are (global) studies on protected areas and their relation to human well-being and social justice (Oldekop et al., 2016; Zafra-Calvo & Geldmann, 2020) that should also be considered. Also, 36% of the investigated articles included aspects of ecosystem services for human well-being into their assessment of protected area effectiveness (Figure 2, Groups A and C), which shows a broadened scope in the field. In this context, UNESCO Biosphere reserves, established for exploring new pathways toward sustainability and directly addressing ecosystem-based strategies to safeguard human well-being, deserve special attention. Biosphere reserves could also be expected to pioneer the implementation and promotion of socially just nature conservation.

While our review design focused on remote sensing approaches, most of the 44 selected studies advocated the inclusion of social science approaches that incorporate the results of studies with the local population, and they cited local participation as one of the most important solutions to increase effectiveness, in addition to expanding the network of protected areas. Occasionally, researchers referred to earlier approaches of effectiveness research and mostly designed their own method to assess this vector, which made it difficult to compare different individual case studies; correspondingly, the findings also support the idea of developing a framework for evaluating effectiveness (Rasheed, 2020; Stephenson et al., 2015). To explore the socio-ecological effectiveness of protected areas and their impact on habitat and species loss, ecosystem services and protection capacity (Beresford et al., 2018)—a more holistic and multi-indicator-based approach—should be considered (e.g., Ghoddousi et al., 2021). The effect of selecting the variables proves relevant, as it influences the results substantially (Beresford et al., 2018; Vanclay, 2001). To select relevant variables, existing studies on essential biodiversity variables (Pereira et al., 2013), biophysical variables (Richter et al., 2012), climate variables (Bojinski et al., 2014), and geodiversity variables (Schrodt et al., 2019) offer a basis on which to build.

Selection methods

The analysis of selection methods within the investigated studies showed that our focus on remote sensing as an explicit method to examine protected area effectiveness helped identify patterns in their different approaches. To estimate the socio-ecological effectiveness of protected areas, indicator values of unprotected and protected areas are generally compared. However, the selection of comparable areas for comparison is rather difficult, albeit it is still highly important. A common selection bias is that protected areas are often established in biodiversity hotspots based on special landscape features, and they are compared with their less diverse surroundings without balancing out this disparity (Beresford et al., 2018; Moreno et al., 2019; Tang et al., 2011). This review represents parts of the debate on the best selection approach, that is, between the inside–outside and matching approaches. Earlier and mostly rather local-scale case studies, using the inside–outside analysis approach with either hard edge borders or an *inside:buffer zone:remote area* ratio, justified the selection of areas directly adjacent to protected areas as having possibly similar biophysical conditions while being aware of a possible bias produced by heterogeneous landscapes (Mtui et al., 2017). However, recent studies using a matching method justified the approach with the bias, because protected areas are not randomly distributed, and most of the time they are located in areas that are either less accessible or of a lower land use value than their surroundings (e.g., Bonilla-Mejia & Higuera-Mendieta, 2019) (Figure 4). Furthermore, to date, there is no common ground on whether designation borders should be considered hard edges or transition areas. Some studies use adjacent areas for comparison (Adeney et al., 2009), while others explicitly exclude them in order to diminish the possible effects of the protected area on them (e.g., "deforestation banned in the reserve spills over to just outside the reserve [...] or isolation spillovers") (Ren et al., 2015).

This review focused on remote sensing approaches, which proved to be successful methods of investigation in all of the selected studies. Nevertheless, the efficacy of this approach is strongly related to the availability and quality of ground-truthing data, not only to test land cover classification, but also for socio-ecological variables and local characteristics. One half of the studies included fieldwork, with some making a clear argument for integrating fieldwork, clearly advocating for ground truthing to clarify anthropogenic activities (Lui & Coomes, 2016; Nagendra et al., 2009). The need to combine local and global monitoring by integrating fieldwork and remote sensing datasets for significant effectiveness statements is clearly visible (Stephenson et al., 2015). However, it has to be proven if local effects of protected areas are visible on a larger scale (Mora & Sale, 2011).

Aside from the spatial scale, temporal dimensions are equally important. The majority of the examined studies used some forms of time series analysis to detect changes effectively over time. Approaches using time series analysis of randomly sampled matching points inside and outside of protected areas are becoming more commonplace (Beresford et al., 2018; Gray et al., 2016). It is a challenging task, though, as multiple factors such as protected area designation, political changes, conflicts, historical context, or population growth have to be considered and are subject to change. Additionally, protected areas are a quite recent phenomenon, and the analysis of effectiveness will be better understood in the future (Moreno et al., 2019).

Prospects

Remote sensing offers tremendous opportunities to examine the land and sea surfaces on various spatial and temporal scales. By taking advantage of new methods and computation technologies such as machine learning and big data analysis, remote sensing can be considered a promising approach to assess the socio-ecological effectiveness of protected areas. A semiautomatic tool for the global assessment of protected area effectiveness, based on a set of appropriate socio-ecological indicators, would help in terms of comparison and support the monitoring and evaluation of global strategies and conventions such as the CBD and the Man and the Biosphere Program, as well as national and supranational biodiversity strategies. However, several questions remain: What indicators should be used to assess the effectiveness of protected areas? Which indicators fit best in terms of region and protection status? And should specific and hard-to-measure indicators such as the genetic diversity of vegetation, the diversity of ecological processes, and the function or the degree of environmental justice be included in assessments?

This study and its results are limited to a certain extent. First, data acquisition was limited to databases listed on the Web of Science. An overview of existing studies, such as the present research, especially if they use large datasets, not only collects information on a topic, but also duplicates uncertainties in the results. The field of protected area effectiveness, and the corresponding spectrum of definitions and theories, is quite a recent research field (this paper's dataset ranges from publishing dates 2004–2019), so research design, definitions, findings, and framework development are in their early stage.

CONCLUSIONS

This paper demonstrates that a globally standardized framework for using remote sensing to assess the socio-ecological effectiveness of protected areas does not currently exist. Several researchers advocate for more holistic approaches on global effectiveness research, which is pending. A global analysis of the effectiveness of protected areas will be a challenging task, mostly due to the demands involved in finding overall matching indicators and reliable data on a global basis. To date, there is not a complete toolset, which incorporates all relevant indicators to assess the effectiveness of protected areas. It is also a question of time and scale to be able to produce global maps of the effectiveness of protected areas while at the same time taking into account local characteristics such as historical context and local and regional environmental management. A global socio-environmental monitoring tool in this regard would not only provide information on the current state of conservation effectiveness around the world, but it would also be valuable to policymakers, stakeholders, and communities seeking to promote sustainable development as a key objective.

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CONFLICT OF INTEREST

The authors declare no conflict of interest.

AUTHOR CONTRIBUTIONS

Charlotte Gohr and Pierre L. Ibisch conceived the study, and Henrik von Wehrden contributed to the methodological development. Charlotte Gohr wrote the original draft and conducted the analyses. All authors were involved in reviewing and revising the draft versions.

DATA AVAILABILITY STATEMENT

Data (Gohr, 2022) are available from Figshare: https://doi.org/10.6084/m9.figshare.17198771.

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