A simple and practical measure of the connectivity of protected area networks: The ProNet metric

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Abstract
Measuring connectivity is key to track progress toward broad conservation goals, such as the United Nations Convention on Biological Diversity’s proposed Post-2020 Global Biodiversity Framework. The framework includes an area-based target for the protection of 30% of lands and seas globally—through well-connected systems of protected areas. Although the field of connectivity science has grown rapidly, limited progress has been made in tracking conservation connectivity in practice. This is in part due to the lack of a standardizing framework to clarify different purposes, approaches, and datasets—particularly in differentiating a metric from its application within a broader connectivity framework—as well as a benchmark to quantitatively compare alternative approaches. To address this science-practice gap, we developed a novel metric of connectivity called the Protected Network metric (ProNet). ProNet is designed to assess the structural connectivity of a protected area network in a way that can be easily described, clearly communicated, and rapidly computed at high resolution. We evaluated how ProNet adheres to fundamental conservation science principles using a library of hypothetical landscapes, compared it to two commonly used existing connectivity metrics, and demonstrated its performance in assessing connectivity for a set of real-world landscapes selected across the gradient of human modification. More broadly, ProNet is a powerful tool to galvanize emerging connectivity conservation as a countermeasure to increasing fragmentation of global ecosystems.

KEYWORDS
30 x 30, area-based conservation, connectivity science, conservation planning, ecological connectivity, human modification, protected area networks

1 | INTRODUCTION

The world is experiencing unprecedented levels of habitat loss and fragmentation (Haddad et al., 2015). In response, national and international conservation efforts are increasingly focused on reaching area-based conservation goals (Maxwell et al., 2020). In particular, negotiations toward the United Nations Convention on
Biological Diversity’s Post-2020 Global Biodiversity Framework (Post-2020 GBF) propose conserving and connecting 30% of land and seas by 2030 (CBD, 2021):

**Target 3.** Ensure that at least 30 per cent globally of land areas and of sea areas, especially areas of particular importance for biodiversity and its contributions to people, are conserved through effectively and equitably managed, ecologically representative and well-connected systems of protected areas and other effective area-based conservation measures, and integrated into the wider landscapes and seascapes.

Eighteen indicators specific to Target 3 have been identified in the proposed Post-2020 GBF and an additional fifteen have been proposed as alternate or additional indicators (CBD, 2022). Which indicator(s) are most suitable and fit-for-purpose continues to be discussed. Thus, there remains a need to enhance measurement of the structural connectivity of protected areas (PAs) and their larger networks, by identifying and implementing a practical metric for this purpose that is globally comprehensive, scalable from regional-to-country-to-global levels, consistent and comparable over time, and easy to communicate and readily calculated. We believe that a primary reason that progress in these discussions has been stymied is because they have conflated metrics with the indicator in which they are used, and have lacked a rigorous, quantitative basis in which to compare connectivity metrics, such as ProtConn (e.g., Protected Planet, Saura et al., 2019; Bargel et al., 2020).

In a review of connectivity metrics, Keeley et al. (2021) proposed a typology with four groups: (1) structural metrics derived from binary maps and non-species specific functions; (2) structural metrics derived from binary maps with species-specific population and dispersal functions; (3) resistance-based functions; and (4) functional species-specific metrics that reflect observations on presence and/or behavior of individuals. Although connectivity is fundamentally a species-specific concept (Watts & Handley, 2010), assessing functional connectivity in practice is inevitably limited to specific species or populations at local extents for which empirical data are available. The data to parameterize species-specific connectivity models (groups 2–4) are sparse at best (Calabrese & Fagan, 2004) and typically limited to endangered or charismatic species (especially birds and mammals, see, e.g., Brennan et al., 2022). Another challenge is that the more a measure of connectivity is focused on a single species, population, or individual organism, the less generalizable it is to other species, communities, timeframes, or landscapes. To assess and compare connectivity globally, structural connectivity metrics (groups 1 and 2) are more feasible, have fewer assumptions (i.e., are parsimonious), are aligned with the needs of broader initiatives designed to guide public policy and conservation decisions (Santini et al., 2016), and provide a strong complement to the valuable indicators that measure functional connectivity (e.g., Brennan et al., 2022).

A connectivity metric should adhere to fundamental conservation science principles and perform well in both hypothetical and real-world landscapes (Hilty et al., 2019). It should allow tracking progress toward meeting connectivity goals and targets and complement measures of the proportion of area protected. It should evaluate landscape context including the variability of the matrix between PAs (Zeller et al., 2012). And, because connectivity metrics are very sensitive to the resolution at which a landscape is represented, trade-offs between computational complexity and modeling resolution should favor measuring connectivity at the highest resolution possible (minimally <1 km²). Most importantly, a connectivity metric should be simple to explain, readily communicated, and easily understood by policy and decision makers, which is critical to bridge the science-practice gap (Theobald et al., 2000).

In discussions about measuring connectivity, it is key to distinguish the metric from the broader indicator in a connectivity framework, which we consider as a series of decisions made, data used, and actions taken when calculating a specific metric. There are six major steps (Figure S1): (1) clearly define the purpose for conducting the connectivity assessment; (2) identify the specific features to be connected; (3) determine the ecological factors affecting the resistance to movement; (4) decide on the ecological assumptions and computational formula used in modeling movement (e.g., Euclidean, least-cost, or random walk); (5) select the metric to quantify connectivity; and (6) generate the output, such as metric values, graphs, and maps. Without a description of these important steps, policy and decision makers are challenged to understand estimates of the connectivity of global terrestrial PA systems and differences between various approaches that have been developed by the scientific community. For example, recent papers presenting results of indicators that measure the connectivity of PAs have found that 7.04 versus 9.7% of PAs globally were connected in 2020 (UNEP-WCMC and IUCN, 2021; Ward et al., 2020). A series of three PA connectivity indicator results suggest a declining trend in PA connectivity: 9% for 2016, 7.7% for 2018, and 7.04% for 2020 (Saura et al., 2017; Saura et al., 2019; UNEP-WCMC and IUCN, 2021, respectively).
However, these estimates are not directly comparable because key aspects of calculating the indicators of connectivity are confounded and differ between publications. In the remainder of this article, we focus on describing the analytical details of a few key connectivity metrics (Step 5), because this is a major source of confusion when understanding, discussing, and evaluating the results of indicators that measure connectivity.

Although many connectivity metrics have been developed and suggested for use in evaluating the connectivity of PA networks, few comparisons—especially quantitative—have been conducted (Saura & Pascual-Hortal, 2007; Ward et al., 2020). Key to deciding on the appropriate use or even selecting a “best” metric for a given purpose requires a library of hypothetical and real-world landscapes that can be used to test, evaluate, and quantitatively compare different metrics (Keeley et al., 2021). This will also assist in the communication of results to practitioners and decision makers influencing policies. Our underlying premise is that tracking connectivity conservation has made limited progress in moving from science into practice, because a simple structural connectivity metric that can be easily described, quickly communicated, and readily computed has not been identified.

1.1 Problem statement

Here, we describe a novel metric of connectivity called the Protected Network metric (ProNet) which is designed to assess connectivity of a PA network, relevant to conservation goals or targets such as Target 3 of the Post-2020 Global Biodiversity Framework. ProNet is intended to be a simple, robust, and extendable metric developed specifically to guide high-level conservation actions and policies by tracking the performance of area-based conservation efforts with respect to the connectivity of a network of PAs. Therefore, our objectives are to: describe a set of criteria to evaluate metrics of PA connectivity; detail and demonstrate the calculation of ProNet; present and compare connectivity metrics using a “library” of hypothetical landscapes as a basis to quantitatively describe, understand, and compare the behavior of metrics; illustrate the use of ProNet to evaluate the connectivity of a PA network for landscape and country-level assessments; and summarize intended uses, limitations/caveats and next steps for applying ProNet to measure connectivity of PA networks.

2 METHODS

Our work consisted of five broad steps, we: (1) review evaluation criteria established for the rigorous measurement of landscape connectivity (described in Table 1); (2) detail the calculation of the ProNet metric; (3) demonstrate its application using a library of hypothetical landscapes designed to test against the evaluation criteria; (4) compare ProNet to two other structural connectivity metrics, ProtConn and ConnIntact; and finally, (5) illustrate the calculation of ProNet using four real-world landscapes. To have a deeper understanding of, and to enable direct comparisons, we needed to disentangle the metric from the overall indicator results provided for ProtConn (Saura et al., 2019) and ConnIntact (Ward et al., 2020) by holding constant the assumptions about what constitutes a feature to be connected, the data used in representing the PA system, and how distance is measured.

2.1 Criteria for connectivity metrics

Building on the work of Saura and Pascual-Hortal (2007) and Jaeger (2000), we present a list of criteria to evaluate desirable properties of metrics (Table 1). Bounded values (property A in Table 1) between 0.0 and 1.0 are needed for unambiguous calculation of indicators (Gardner & Urban, 2007; Schultz, 2001). Decreases in connectivity values with increases in interpatch distance (Property B), increased fragmentation (Property C), loss of an isolated patch (Property D), loss of patch area (Property E), and an increased number of clusters (Property F) are consistent with the theory of island biogeography (MacArthur & Wilson, 1967; Saura & Pascual-Hortal, 2007). When a landscape is fully protected (Property G), the value of a metric should reach its maximum, indicating a fully connected area; if the connectivity value were 0 in a fully protected landscape it would falsely equal the condition of a landscape without any PAs and therefore indicate no connectivity (Saura & Pascual-Hortal, 2007). This argument also applies to explicitly measuring within-patch (PA) connectivity (Property H), which is key to recognizing the diversity of scales at which processes occur.

A metric must be able to be readily calculated (i.e., within a few weeks) to measure changes in connectivity due to rapidly changing landscape conditions at national-to-global extents with a spatial resolution that resolves critical features causing fragmentation (Property I). It needs to be able to take advantage of the increasing availability of remotely sensed essential biodiversity variables, especially regarding ecosystem structure (Jetz et al., 2019). Finally, to be of practical value and actually be applied to inform conservation, the metric and its results must be simple to describe and readily communicated (Property J) to an important audience: policy and decision makers, though we recognize evaluating this criterion can be subjective and context dependent.
2.2 Metrics comparison

An exhaustive comparison of all possible metrics (see Keeley et al., 2021) is beyond the scope of this article. Instead, we compared ProNet to two other metrics (ProtConn and ConnIntact; SI Table 1) that have been identified as indicators specifically associated with Target 3 in recent CBD documents (e.g., CBD, 2022), and that are relatively easy to replicate and calculate for landscapes with a limited number of PAs (e.g., <C2410). ProtConn uses graph theory to calculate the probability of connectivity of a PA (patch) to all other patches in a landscape, and within a maximum distance (Saura et al., 2017; Table S1). ConnIntact is a modification of ProtConn that assumes two patches are connected if they are both within a contiguous “intact” region defined by minimal levels of human pressures (Ward et al., 2020; Table S1), regardless of the distance between the patches, and that removes consideration of intrapatch connectivity that is incorporated into ProtConn. Even though the PA Representativeness and Connectedness index (https://www.bipindicators.net/indicators/protected-area-connectedness-index-parc-connectedness) is also associated with Target 3, we did not compare it to ProNet because the metric does not evaluate connectivity specifically from a PA to other PAs and confounds the proportion of PA with primary vegetation from land cover data. We also did not include metrics in the comparison that measure spatial structure or the general spatial context of habitat quality, because they evaluate different conservation objectives (e.g., Goal A, CBD, 2021; Nicholson et al., 2021) than the connectivity among PAs per se. Examples are landscape integrity/intactness metrics (e.g., Beyer et al., 2020; Blumetto et al., 2019; Ferrier et al., 2020; Grantham et al., 2020;)

| Property                          | Description of property                                                                 | Test landscape values  | ProNet | ProtConn | ConnIntact |
|-----------------------------------|-----------------------------------------------------------------------------------------|------------------------|--------|----------|------------|
| A. Bounded and linear values      | Values are bounded between 0 and 1, or a real data type and represent a linear distribution. | 0.0 ≤ L1–25 ≤ 1.0      | +      | +        | +          |
| B. Interpatch distance            | Values decrease when distance between patches increases or exceeds a distance or dispersal threshold, which can include variation in matrix quality. | L9 > L5; L10 > L6; L11 > L7; L12 > L8; L17 > L15 > L13; L25 > L24 > L23 > L22 | +      | +        | x          |
| C. Fragmentation                  | Values decrease when a patch is bisected (fragmented) into two or more patches (all other things being equal). | L4 > L8                | +      | +        | x          |
| D. Loss of isolated patch         | Values decrease when an unconnected patch is removed.                                    | L9 > L15               | +      | +        | +          |
| E. Loss of patch area             | Value decreases when the area of a patch decreases, and decreases more with larger area loss. | L7 > L6 > L5           | +      | +        | x          |
| F. Increase in clusters           | Value decreases more when removal of an edge results in an increase in the number of clusters (subcomponents). | L17 > L15; L25 > L24 > L23 | +      | +        | +          |
| G. Landscape fully protected      | Value reaches its maximum when a single patch occupies the full landscape.               | L4                     | +      | +        | x          |
| H. Within-patch connectivity      | Value reflects within-patch connectivity as well as between-patch connectivity.         | L1, L2, L3, L4 > 0.0   | +      | +        | x          |
| I. Detailed resolution and computational efficiency | Calculating the metric is computationally efficient so that high resolution (<1 km²) maps that adequately represent linear fragmenting features, such as roads, can be readily computed. | –                     | +      | x        | x          |
| J. Simple and intuitive           | Simple to describe, calculate, and communicate, with intuitive results.                | –                      | +      | x        | –          |
Theobald, 2013) and more general measures of landscape fragmentation (e.g., effective mesh size, Jaeger, 2000).

### 2.3 The ProNet metric

ProNet is calculated as:

\[ \text{ProNet} = \frac{\sum_{k=1}^{m} \left( \sum_{i=1}^{n} a_{ik} \right)^{2}}{\left( \sum_{i=1}^{n} a_{i} \right)^{2}} \]

where \( a \) is the size of PA (patch) \( i \) for \( n \) PAs. Each PA \( i \) is grouped within cluster \( k \) of \( m \) clusters (aka a component of a network in graph theory). Essentially, ProNet is calculated as the sum of the squared areas of PAs within each cluster, normalized by the square of the sum of areas for all PAs. Thus, values range from 0.0 (unconnected) to 1.0 (fully connected), and the metric depends only on the PA network found within a defined landscape and so is not sensitive to the area of the encompassing landscape. Figure 1 illustrates a worked example.

An important first step when calculating ProNet (and other metrics) is to define what constitutes connected PAs: that is, which PAs form a cluster. Clusters are formed when a distance criterion is met, and distance can be defined using a variety of resistance assumptions and movement types. These need to be specified prior to calculating a metric. Generally, we define a cluster as a set of PAs within a specified distance, \( d \), of one another (e.g., 10 km from edge-to-edge). Using graph theory, each cluster is a component of a network with the condition that it is constrained to the landscape surface, resulting in a minimum planar graph (Fall et al., 2007). Conceptually, this means that sets of PAs are treated as a simple network where PAs are connected directly with nearby PAs and indirectly to more distant PAs through the network itself. Ecologically, this is consistent with the definition of an ecological neighborhood (Addicott et al., 1987) and the first law of geography (Tobler, 1970), so that movement across a landscape occurs as a sequence of individual decisions influenced by the landscape condition of the immediate surrounding. Practically, this greatly reduces the exponential computational load from measuring \( n^2 \) distances between PAs (nodes) to \( n \), where \( n \) is the number of PAs, and avoids restrictive computation times as the number of PAs increase. It results in an efficient and interpretable visual representation of the network (Fall et al., 2007) that is particularly valuable for conservation planning (Bunn et al., 2000). It also greatly reduces the time required to analyze the network, which in turn allows greater fidelity to the full set of PAs because smaller PAs can be included in the analysis, rather than using a minimum area threshold that removes many PAs from the analysis. We also note that a range of connectivity distances can be easily explored through multiple runs (e.g., as illustrated by Urban & Keitt, 2001).

Distance \( d \) can be measured as an “ecological distance” that reflects assumptions about the resistance of the matrix to movement between PAs. In the analyses described below, the ecological distance reflects unconstrained movements (“flying”) and is therefore equivalent to the Euclidean distance. We used a range of distances (i.e., 10, 30, and 100 km) to approximate the movement abilities of different terrestrial species (following Saura et al., 2017). We note that, alternatively, ProNet can be calculated using “ecological distances” to represent assumptions of movements constrained to the land surface (i.e., walking), or constrained to water (i.e., swimming). Ecological distance can be based on either structural landscape characteristics such as low human modification (Kennedy et al., 2019) or functional aspects (e.g., dispersal probability as a function of body size, vagility, or species-specific capabilities or behavior). Models of movement across resistance surfaces typically include least-cost path (Adriaensen et al., 2003; Etherington, 2016), least-cost distance (Theobald, 2006), random-walker (McRae, 2006), or randomized short-paths (e.g., Williamson et al., 2020).

### 2.4 Hypothetical and case-study landscapes

To facilitate a quantitative evaluation of metrics, we developed a set of 25 hypothetical landscapes, each with a distinct combination of PAs that vary in number, size, and
The configuration of 25 hypothetical landscapes with results of three connectivity metrics—ProNet, ProtConn (Saura & Pascual-Hortal, 2007), and ConnIntact (Ward et al., 2020)—are provided to illustrate the use of this “library” of landscapes for clearer evaluation of their uses and differences. Blue lines between protected areas (PAs) in L9–L12, L15–L21, L23–L25 denote a connection between PAs. As in the figure, the area of the small, medium, and large patches (i.e., landscape 1, 2, and 3) are assumed to be 1, 3, and 10 km² and the full landscape 46.5 km². PAs in L8 and L12, are 10.0 and 36.4 km² (left and right). While difficult to see, in L8, the PAs are isolated; in L12, the PAs are connected.

For each of the four landscapes, we used the World Database on PAs (UNEP-WCMC and IUCN, 2021) to identify PAs for inclusion within the PA network (step 1 in Figure S1). We preprocessed the PA features consistent with previous global analyses (e.g., Saura et al., 2017, 2018). Specifically, we included any terrestrial PA when its status was designated or established, not a World Heritage Site, and >0.09 km². PAs represented as points in the WDPA (e.g., because precise polygonal boundaries are not available) were converted to circles equal to the area of that PA. Only 2% of the ~12,000 points had area estimates (globally); PAs without area estimates were excluded. PA polygons that overlapped or shared a common border effectively function as a single entity. Therefore, we converted the polygons to a raster dataset that results in “flattened” and contiguous regions of PAs.

Another decision point when calculating connectivity concerns the exclusion or inclusion of PAs just outside the area of analysis. Excluding cross-boundary (e.g., international) PAs limits the measurement of connectivity to those PAs within a government’s jurisdiction, while including PAs that occur outside a
country could better reflect ecological connectivity assuming that animals, plants, and ecological processes are able to cross borders. In our case studies, to keep the results focused, we ran the interior-only (not cross-boundary) scenario.

3 | RESULTS

We found that the metrics evaluated met most of the desirable conditions of a connectivity metric (Table 1). ProNet met all criteria, ProtConn met all but the computational and communication criteria (Properties I and J), while ConnIntact met only criteria A, D, and F (and arguably I).

We found that the values for all three metrics were well-bounded between 0.0 and 1.0 (or 0–100%) for all test landscapes (L1–L25). This allows results to be expressed in a graph showing how different landscapes are placed within a percent-protected versus percent-connected plot (Figures 3 and S2–S5). The landscapes measured by ProNet and ConnIntact generally show a regular and

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**FIGURE 3** Case-study landscapes for which ProNet was applied. Protected areas are shown in unique colors and grouped into clusters based on a 30 km straight-line threshold distance, for: (a) Costa Rica, (b) India, (c) Pantanal-Chaco landscape in Argentina, Bolivia, and Paraguay, and (d) the southern Kenya-northern Tanzania landscape (top left, top right, bottom left, bottom right). (Maps are drawn at different scales).
consistent pattern, which contrasts with ProtConn results that follow a nonlinear distribution (compressed at low levels of % area protected, Figure S2), which is consistent with its formulation of estimating both landscape aspects, connected and protected, in a single value. We list specific observations on ProNet here.

A. ProNet is consistent with the theory of island biogeography and metapopulation dynamics (Hanski, 1999) that states that interpatch distance (and patch area, see I below) affect species diversity and population sizes. Values for test landscapes are consistent with expectations, particularly that: L7 < L4; L5 < L9; L6 < L10.

B. ProNet values decrease substantially when a patch is fragmented: L8 < L4 and L12.

C. When an isolated, unconnected patch is removed, the ProNet value increases: L13 < L5 < L1.

D. The ProNet value decreases when the area of a patch decreases without an increase in fragmentation (i.e., the number of patches remains the same) and without a change in the number of clusters (components): L5 < L6 < L7; L13 < L14; L15 < L16. This is consistent with fractal/percolation theory that places greater weight on larger patches, such as the weighted mean patch index (Li & Archer, 1997). The ProNet value for a landscape with a single cluster (all patches are connected) is always 1.0.

E. The ProNet value decreases when there is an increase in the number of clusters: L5 < L9; L15 < L17 and L19; L22 < L23 < L24 < L25.

F. The value of ProNet is 1.0 when a landscape is fully protected—that is, a landscape is covered by a single PA (or multiple PAs that border each other): L4.

G. The ProNet value reflects within-patch connectivity in addition to between-patch connectivity: L4; L5 < L6 < L7; L13 < L14.

H. The algorithmic complexity of ProNet is minimal so it can be readily computed for PA networks with large extent (i.e., countries/continents) and high resolution (<1 km²). This is critical to adequately represent features important for connectivity analyses. Real-world features that potentially fragment landscapes must be adequately represented in the datasets used to calculate a connectivity metric, especially narrow linear features like highways, railways, and energy infrastructure.

I. ProNet is simple to describe mathematically, graphically, and verbally so that it is readily communicated with policy and decision makers who are applying the metric in practice (Figure S2).

In all four illustrative landscapes, ProNet values are similar for the 10 and 30 km threshold distances, and higher for the 100 km threshold distance (Table 2, Figure 4). ProNet values vary among study landscapes, TABLE 2 ProNet values of protected area networks in four study landscapes calculated with three threshold distances used to define clusters. The percent of the study landscape protected is included because it provides important context for interpreting connectivity and area-based targets such as Target 3 from the Convention on Biological Diversity’s Post-2020 Global Biodiversity Framework.

| Study landscape                  | Threshold distance (km) |       | Percent of study landscape protected |
|---------------------------------|-------------------------|-------|-------------------------------------|
|                                 | 10                      | 30    | 100                                 |
| India                           | 0.143                   | 0.145 | 0.306                               | 0.45                     |
| Pantanal-Chaco (South America)  | 0.108                   | 0.123 | 0.320                               | 4.50                     |
| Costa Rica                      | 0.362                   | 1.000 | 1.000                               | 22.20                    |
| Southern Kenya-Northern Tanzania| 0.429                   | 0.499 | 0.998                               | 27.21                    |

FIGURE 4 Percent of study area protected versus percent of protected areas connected, as measured by ProNet, for the four case study areas (from left to right: India, Pantanal-Chaco, Costa Rica, and Southern Kenya-Northern Tanzania). The different colors indicate the distance thresholds (10, 30, and 100 km) under which protected areas (PAs) are considered connected.
even in the two large, intact landscapes (Pantanal-Chaco and Southern Kenya-Northern Tanzania), and range from 0.108 to 0.428 with the 10 km threshold distance.

4 | DISCUSSION

ProNet is a simple, useful, and robust metric to quantitatively measure the connectivity of PA networks. It meets the properties and conditions critical for connectivity metrics that have been developed in the field of landscape ecology and are supported by the conservation science literature. It yields easy-to-interpret results when applied to landscapes across the gradient of human modification. It is particularly well-suited to inform the degree to which area-based conservation targets meet the requirement of being “well-connected.”

Two scenarios can help with interpreting the results of the three metrics we compared (also see Figures S3-S5). First, as additional PAs that are the same size but not connected are added to a system (the sequence L1, L5, L13, and L22, Figure 2), ProNet indicates that connectivity decreases from 1.0 to 0.5 to 0.3 to 0.01 because, despite additional area, the PA system is gaining more elements which are isolated from each other. In contrast, the ConnIntact value for all landscapes is 0.0 because the metric does not account for intrapatch connectivity; ProtConn values increase nonlinearly in these four hypothetical landscapes (0, 0.001, 0.0001, 0.003), with small differences controlled by the normalization of the overall landscape area. A second scenario is an increasing number, and total area, of connected PAs (the sequence of L1, L9, L19, L25). ProNet measures all of these as fully connected (ProNet = 1.0), whereas ConnIntact jumps from 0.0 (for a single PA: L1) to 1.0 (L9, L19). Fully connected networks have a higher ConnIntact value (e.g., L19: 1.0) than minimum planar graphs (e.g., L25: 0.7; if fully connected, L25 would have 30 edges between PA nodes instead of 9 edges). ProtConn values increase with an increase in the number of PAs, but stay very low (0.0, 0.002, 0.004, 0.011). Also, ProtConn is normalized by a geographical unit (e.g., country), whereas ConnIntact and ProNet are not. Having separate metrics for PA network connectivity and for the proportion of area protected greatly eases interpretation and comparison. Therefore, we recommend reporting both the ProNet value and the proportion of area protected (Figure 4). Increasing the number or size of PAs, connecting existing PAs, or taking both actions will increase connectivity, the percent of area protected, or both. Although more detailed conservation strategies/actions around connectivity conservation have been identified (e.g., Cameron et al., 2022), we illustrate in Figures S6-S10 combinations of protecting, connecting, restoring, and protecting/connecting.

In this analysis, we considered only the straight-line, edge-to-edge distance between PAs and threshold values to determine whether a pair of PAs is connected (Figure S11). A future analysis could take into account the variability of the matrix quality between PAs: the straight-line distance can readily be replaced with an ecologically relevant distance (e.g., Adriaensen et al., 2003; Theobald, 2006). This would allow the consideration of human land use and linear infrastructure (Kennedy et al., 2019; Theobald et al., 2020) when deciding whether PAs are part of a cluster. We recommend that future work estimate structural connectivity based on high-resolution (<300 m) estimates of naturalness (Theobald, 2013), which assumes that many species are able to move fairly through intact lands (Ward et al., 2020) or move more easily through natural lands than through areas heavily impacted by human activities (Keeley et al., 2021; Krosby et al., 2015). Naturalness approaches have been used to inform coarse-filter conservation strategies such as the potential to support range shifts in response to climate change (McGuire et al., 2016; Parks et al., 2020; Schloss et al., 2021). Additional work should apply ProNet to measure ecosystem and species-specific functional connectivity of PA networks (e.g., Magle et al., 2009; Naidoo et al., 2018), and assess the metric’s potential to evaluate conservation planning scenarios of land use and/or climate change alternatives (e.g., Williamson et al., 2020) or for use in reserve design using optimization frameworks.

Unlike most other measures of landscape pattern and ecological intactness, connectivity and fragmentation metrics are especially sensitive to representation and resolution issues. Therefore, an important decision when measuring connectivity of PA networks is which PAs to include in the analysis (Santini et al., 2016; Figure 1, step 2). Including smaller PAs is desirable because small or narrow PAs can be ecologically and/or socio-politically important and commonly results in higher network-wide connectivity values. However, including smaller PAs (which often are many times more numerous than larger PAs) can increase computational demands by an order of magnitude or more, particularly in broad-extent landscapes. The minimum size of PAs included in an analysis is typically controlled by the resolution of the datasets used in the analysis and varies from 0.09 km² (this study), 1 km² (Saura et al., 2017), 10 km² (Ward et al., 2020) to 35 km² (Brennan et al., 2022). Measuring connectivity accurately requires a resolution at which restrictions or barriers to movement (e.g., highways) can be represented. Depicting them properly at coarse resolutions (>100–300 m) is deficient because the infrastructure features themselves are typically only 10–50 m wide. The standard for calculating surfaces that represent resistance to movement takes the arithmetic average of the mixture of land uses and infrastructure (often mapped at higher
resolution, e.g., 30 m land cover). For example, a highway 30 m wide crossing a 1 km² pixel occupies only 3% of the area. The arithmetic average would substantially underestimate the resistance, which can lead to incorrect analyses (Theobald, 2006) and even misidentify the location of movement corridors (Etherington, 2016). Creating resistance surfaces at the highest resolution possible is the best solution. Using, for example, 90–300 m resolution human modification data (available nationally and/or globally, Theobald et al., 2020) can result in a 3- to 30-fold improvement of the resistance estimate over 1–10 km² resolution.

We recognize that ProNet may be limited for some potential needs of measuring connectivity. In some situations and landscapes it may be important to account for redundancy of ecological corridors between PAs (Theobald, 2006; Urban & Keitt, 2001), which can be characterized, for example, through centrality measures (e.g., Carroll et al., 2012; Theobald et al., 2012) or by identifying regions of diffuse and concentrated ecological flow (Schloss et al., 2021). To reduce the complexity in interpreting results and reduce computational demands, we defined a cluster by the minimum planar graph. This approach retains the ability to characterize the effect of distance between PAs (i.e., B in Table 1; in contrast to ConnIntact; Ward et al., 2020). ProNet values decrease when distance between patches exceeds a distance threshold, which can include variation in matrix quality. We also make the simplifying assumption in ProNet that two PAs are either connected or not connected (as was done in Pascual-Hortal & Saura, 2006). Ecologically, this is likely more appropriate when considering PA systems with large patches separated by longer distances. Representing the probability of connection (e.g., based on dispersal distance), as was introduced in Saura and Pascual-Hortal (2007), is likely more appropriate for systems where “stepping stone” patches may be more common such as in the case when patches are defined by a species’ habitat. Future efforts would be improved by evaluating the gain provided by including indirect linkages, similar to efforts that have normalized estimates of ecological distance by simple Euclidean distance (e.g., Schloss et al., 2021).

We urge additional systematic comparisons of ProNet with other metrics to identify strengths, weaknesses, and appropriateness of all metrics. This would include the variety of decisions made within the connectivity framework prior to applying the metric, as well as in the context of different purposes to characterize the PA network itself, its configuration within the landscape, and the connectivity benefits of adding PAs, including smaller “stepping-stone” patches.

In addition to measuring the connectivity of PAs per se, ProNet can be used to estimate the connectivity of PA networks including other effective area-based conservation measures (OECMs), which are being increasingly formalized and delineated (Gurney et al., 2021). It can also be used with other areas important to protect biodiversity, such as natural area patches or key biodiversity areas (e.g., Plumptre et al., 2019). The condition or intactness within a PA can also be accounted for by adjusting the size based on its habitat quality or a measure of naturalness (e.g., the degree of human modification; Theobald et al., 2020). Finally, ProNet should be evaluated to potentially identify ecological networks for conservation (Hilty et al., 2020; Hilty & Laur, 2021), defined as “a system of core habitats (PAs, OECMs, and other intact natural areas), connected by ecological corridors, which is established, restored as needed, and maintained to conserve biological diversity in systems that have been fragmented” (Hilty et al., 2020, p. 4).

5 | CONCLUSION

We described a novel metric that measures the structural connectivity of PA networks. It is simple, rigorous, and practical for measuring and tracking conservation performance. We supported our assessment of ProNet by demonstrating that it meets all criteria desirable for a connectivity metric. To this end, we designed hypothetical landscapes that represent a series of network configurations and calculated the connectivity values. In addition, we believe that the library of conceptual landscapes put forth here fills a critical gap in facilitating a rigorous and quantitative approach to evaluate and compare existing and new metrics, which we encourage the scientific community to apply and expand on. We have argued that with its simple formulation, consistent results, and rapid computation, ProNet is a useful metric that can be applied to monitor changes in connectivity over time, compare the level of connectivity of different PA networks, and inform decision making in practice (Theobald et al., 2000).

We reiterate that calculating a metric is only one of six major steps necessary to measure a connectivity indicator, each of which requires selection from a range of options (Figure S1). Understanding the effects of all decisions made when measuring connectivity is key to assessing the advantages and disadvantages of different approaches and selecting the approach that best aligns with the intended purpose. Conservation scientists can then make appropriate and timely recommendations to policy makers tasked with tracking conservation performance toward goals and targets.

We conclude that ProNet is a valuable and important contribution to reporting progress toward meeting
connectivity goals and targets established or proposed, such as by the Post-2020 Global Biodiversity Framework of the Convention on Biological Diversity and the America-the-Beautiful initiative launched in the United States (Executive Order 14008). Continued progress toward achieving conservation goals (e.g., a well-connected 30% of PAs) will require more rigorous evaluation of connectivity toward broader conservation targets, which will be expedited by using this simple, robust, easy to communicate metric. This will provide more precise, consistent, comprehensive, and comparable results to track and report progress at global, national, and subnational levels.

Connectivity conservation is an emergent realm of conservation practice—one that is growing mainstream as a countermeasure to increased fragmentation of ecosystems globally. As countries respond to the challenge of establishing well-connected systems of PAs covering at least 30% of their territory, we believe that ProNet will be valuable in providing a consistent, comparable, and practical measure of connectivity.

AUTHOR CONTRIBUTIONS
David M. Theobald developed the research question, conducted the data analysis, wrote the first draft of the manuscript, and revised the manuscript. Annika T. H. Keeley codeveloped the research and contributed to analysis, writing, and development of figures. Aaron Laur and Gary Tabor codeveloped the research question and reviewed and edited the manuscript. All authors approved the submitted version.

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CONFLICT OF INTEREST
The authors declare that there is no conflict of interest that could be perceived as prejudicing the impartiality of the research reported.

DATA AVAILABILITY STATEMENT
The datasets (shapefiles) that specify the test landscapes are available at: https://doi.org/10.5281/zenodo.7093982. The Google Earth Engine script to generate the landscapes is available at: https://code.earthengine.google.com/d1a8dafa3202ac8b4e55657bd3b5a1160.

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