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LETTER

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Ecosystem extent is a necessary but not sufficient indicator of the state of global forest biodiversity

Simon Ferrier[1] | **Chris Ware**[2] | **Jenet M. Austin**[1] | **Hedley S. Grantham**[3,4,5] | **Thomas D. Harwood**[1,7] | **James E. M. Watson**[6]

[1]CSIRO Environment, Canberra, Australian Capital Territory, Australia

[2]CSIRO Environment, Sandy Bay, Tasmania, Australia

[3]Wildlife Conservation Society, Global Conservation Program, Bronx, New York, USA

[4]Bush Heritage Australia, Melbourne, Victoria, Australia

[5]Centre for Ecosystem Science, School of Biological, Earth and Environmental Sciences, University of New South Wales, Sydney, New South Wales, Australia

[6]Centre for Biodiversity and Conservation Science, School of the Environment, University of Queensland, Brisbane, Queensland, Australia

[7]Environmental Change Institute, University of Oxford, Oxford, United Kingdom

Correspondence
Simon Ferrier, CSIRO Environment, Canberra, ACT, Australia.
Email: simon.ferrier@csiro.au

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Abstract

The Kunming-Montreal Global Biodiversity Framework lays out an ambitious set of goals and targets aimed at halting and reversing biodiversity loss. The extent of natural ecosystems has been selected as one of a small set of headline indicators against which countries will report progress under this framework. We evaluate the effectiveness with which this indicator is expected to capture the overall scope of the ecosystem-focused component of Goal A, and interlinkages with the species-focused component of this same goal, using extensive global data on the integrity, connectivity, and plant species composition of forests. Results generated for all forest-supporting countries demonstrate that consideration of these additional factors can profoundly alter understanding of the state of forest biodiversity relative to that based on extent alone. Employment of ecosystem extent as a headline indicator must therefore be augmented by appropriate use of component and complementary indicators addressing other key dimensions of ecosystem change.

KEYWORDS
biodiversity, forest, global, goal, indicator, state, targets

1 | INTRODUCTION

The Kunming-Montreal Global Biodiversity Framework (GBF), adopted by the 15th Conference of the Parties to the Convention on Biological Diversity (CBD), lays out four long-term goals relating to the 2050 Vision for Biodiversity—“by 2050, biodiversity is valued, conserved, restored and wisely used, maintaining ecosystem services, sustaining a healthy planet and delivering benefits essential for all people.” The GBF also lays out 23 targets specifying the actions required over the remainder of this decade (to 2030) to progress effectively toward achievement of the 2050 goals (CBD, 2022a). Now that the GBF has been adopted, attention is shifting rapidly from the formulation of goals and targets to the challenge of implementing actions to achieve real change against these aspirations.

Indicators will play a key role in monitoring progress toward the achievement of the agreed goals and targets at both national and global levels (CBD, 2022c) and in planning further actions to address shortfalls in this achievement, including through National Biodiversity Strategies and Action Plans (NBSAPs) (CBD, 2022b). The indicators that are likely to attract most attention are those now formally recognized by the CBD as headline indicators—that is, "a minimum set of high-level indicators, which capture the overall scope of the goals and targets of the Kunming-Montreal global biodiversity framework to be used for planning and tracking progress" (CBD, 2022c). All Parties to the CBD will be required to report progress against these headline indicators as part of their reporting obligations under the GBF (CBD, 2022b). This mandatory reporting of headline indicators can optionally be supplemented by the reporting of indicators selected from two other groups of metrics—component indicators (covering all components of the goals and targets) and complementary indicators (supporting thematic or in-depth analysis) (CBD, 2022c). The GBF monitoring framework therefore recognizes that "the headline indicators may not capture all components of a goal or a target but for analytical purposes can be complemented, as appropriate, with the component and complementary indicators" (CBD, 2022c).

Two headline indicators have been identified for monitoring progress in relation to the ecosystem-focused component of Goal A of the GBF—that is, "The integrity, connectivity and resilience of all ecosystems are maintained, enhanced, or restored, substantially increasing the area of natural ecosystems by 2050" (CBD, 2022a). One of these headline indicators is "A.2 Extent of natural ecosystems" (CBD, 2022c). Although monitoring of change in ecosystem extent clearly has an important role to play in assessing the progress of the GBF, concerns have been raised that such an indicator, on its own, will address only one of several key dimensions of ecosystem change, including those identified in Goal A (Belote et al., 2020; Grantham, Duncan et al., 2020; Hansen et al., 2021; Nicholson et al., 2021; Rogers et al., 2022). In the terrestrial realm, changes in the "integrity, connectivity and resilience" of ecosystems may not be adequately reflected by an indicator reporting only the extent (total area) of those systems derived, for example, from the mapping of discrete land-cover classes through remote sensing.

Focusing exclusively on ecosystem extent may also limit capacity to account for important flow-on impacts that any change in the state of ecosystems is likely to have on the species- and genetic-level components of Goal A—that is, "Human induced extinction of known threatened species is halted, and, by 2050, extinction rate and risk of all species are reduced tenfold and the abundance of native wild species is increased to healthy and resilient levels" and "The genetic diversity within populations of wild and domesticated species, is maintained, safeguarding their adaptive potential" (CBD, 2022a). For example, reporting changes in the extent of broad ecosystem types (e.g., forests) may convey little about expected impacts on the persistence of species dependent on these systems, without simultaneously considering how persistence will also be affected by the integrity and connectivity of the areas of habitat making up this overall extent, and by the spatial distribution of these areas relative to how individual species are distributed within the ecosystem. Accounting for these flow-on impacts takes on particular importance when one considers that area-based actions under GBF Targets 1 (spatial planning), 2 (restoration), and 3 (protection) will contribute to achieving outcomes for species and genetic diversity largely through changes in the state of ecosystems (Nicholson et al., 2021).

These other dimensions and potential impacts of ecosystem change can be addressed, at least to some degree, by the other headline indicator identified for monitoring progress in relation to the ecosystem-focused component of Goal A—"A.1 Red List of Ecosystems" (CBD, 2022c). However, given that a sizeable proportion of the world's regions and ecosystem types are yet to undergo Red List of Ecosystems assessment, and that detection of trends in this indicator will require repeated assessment over time (Nicholson et al., 2021), it seems likely that for some years to come many countries will be limited to reporting progress against the ecosystem-focused component of Goal A largely in terms of changes in ecosystem extent alone (headline indicator A.2).

Here we evaluate the effectiveness with which ecosystem extent can be expected to capture the overall scope of the ecosystem-focused component of Goal A and, therefore, the level of need to supplement this indicator with assessments of component and complementary indicators addressing other dimensions of this scope for use in both planning and monitoring. We address this question using state-of-the-art data on all of the world's forests, the broad ecosystem type (or biome) currently attracting particular attention from major global initiatives and agreements complementing the GBF, including the Bonn Challenge and New York Declaration on Forests (Stanturf & Mansourian, 2020), and the Glasgow Leaders' Declaration on Forests and Land Use (Nasi, 2021). We compare results obtained when we assess the state of forests in each of the world's forest-supporting countries using data on forest extent alone with those obtained if we further consider forest integrity and connectivity and the effect that these three attributes, in combination, are expected to have on the persistence of species diversity within these forests.

2 | METHODS

Our approach to addressing these additional factors builds on existing high-resolution mapping of the Forest Landscape Integrity Index (FLII), a globally consistent measure of the state of forest ecosystems estimated from best available spatial data and analysis (Grantham, Duncan et al., 2020), which is itself now recognized as a complementary indicator for Goal A of the GBF (CBD, 2022c). The FLII already integrates consideration of ecosystem extent, integrity, and connectivity at 300 m grid-resolution globally by combining data on forest extent, and a wide range of human pressures, observed or inferred from remote sensing and spatial mapping (Grantham, Duncan et al., 2020).

Any use of remote sensing to map ecosystem attributes such as these assumes a reasonably strong correlation between remotely estimated values for a given attribute (e.g., integrity) and actual values of this attribute on the ground (Hansen et al., 2021). Although the FLII is still a relatively new dataset, available comparisons with ground-based biological and ecological data have yielded encouraging results (Dias et al., 2023; Lee et al., 2024). Given that the FLII incorporates considerable refinement of methods previously used to derive the Human Footprint Index (see Supporting Information), further confidence in the biological meaningfulness of the FLII can also be drawn from a range of studies reporting correlations between mapped values of the Human Footprint and spatial variation in observed species extinction risk (Di Marco et al., 2018; Ocampo-Peñuela et al., 2022; Pillay et al., 2022; Zhou et al., 2024).

To address the expected interdependency between outcomes for the ecosystem- and species-focused components of Goal A, we couple the FLII with the analytical approach underpinning an existing habitat-based biodiversity indicator—the Biodiversity Habitat Index (BHI) (Di Marco, Harwood et al., 2019; Hansen et al., 2021; Hoskins et al., 2020; Soto-Navarro et al., 2020; UNEP WCMC, 2024), also recognized as a component indicator for Goal A (CBD, 2022c). Habitat-based indicators predict the level of species diversity expected to be retained, or to persist, within a given spatial reporting unit as a function of the state and configuration of natural ecosystems, or "habitat," across that unit (Ferrier, 2011; UNEP WCMC, 2016).

It is important to be clear here as to the role that indicators of this type can potentially play in the implementation of the GBF. They are not designed, nor intended, to monitor and report change in the species-focused component of Goal A, as, unlike the well-established headline indicator for this component, the Red List Index, they purposely focus on just one of the multiple drivers of species-level biodiversity loss. However, by adopting this particular focus, habitat-based indicators offer a means to better consider how changes in the integrity and configuration of habitat at an ecosystem level—including through area-based actions implemented under GBF Targets 1–3—are expected to impact outcomes at the species level of Goal A.

Habitat-based indicators can be derived either through bottom-up aggregation of separate analyses of the availability of suitable habitat for individual species or, as in the case of the BHI, through top-down assessment of the expected impact of overall habitat losses and gains on the persistence of species diversity at a whole-community level (Ferrier & Drielsma, 2010). Community-level indicators offer a tractable means of assessing actions and outcomes under the GBF for a larger proportion of the planet's species-level diversity than is currently possible using a species-by-species approach. They are intended to complement, rather than compete with, indicators working more directly with species-level information.

As for most manifestations of the community-level approach, the BHI uses the species–area relationship—widely regarded as ecology's most "basic law" (Rosenzweig, 1999)—to predict the proportion of native species expected to persist as a function of the proportion of natural habitat remaining within a given spatial reporting unit. However, in contrast to other applications of this general approach, for example (Luby et al., 2022), the BHI accounts rigorously for fine-scaled spatial variation both in habitat condition, and in the species composition of communities, across the unit of interest. The BHI has been implemented previously across the entire terrestrial surface of the planet at 30-arcsec grid-resolution (approximately 900 m at the equator), using generalized dissimilarity modeling of spatial variation (beta-diversity) in the species composition of communities and habitat-condition surfaces inferred from downscaled land-use mapping (Di Marco, Harwood et al., 2019; Hansen et al., 2021; Hoskins et al., 2020; Soto-Navarro et al., 2020; UNEP WCMC, 2024). In a recent comparative evaluation of global biodiversity indicators (Stevenson et al., 2024), ecoregional results for this global implementation of the BHI were significantly correlated with those for the Red List Index (of species), exhibiting a level of correlation higher than that between the Red List Index and any of the other ecosystem-level indicators evaluated, including the Human Footprint.

For the analysis presented here, we rederived the BHI for all of the world's forests using the existing beta-diversity modeling of vascular plants (based on data for over 254,000 species globally) (Hoskins et al., 2020), but employing mapping of the FLII for 2019 (Grantham, Duncan et al., 2020) as a refined measure of forest ecosystem integrity in place of the land-use-based condition mapping used in the previous global implementation of the BHI (Hoskins et al., 2020; UNEP WCMC, 2024). We then used this refined BHI approach to predict, for each of the world's forest-

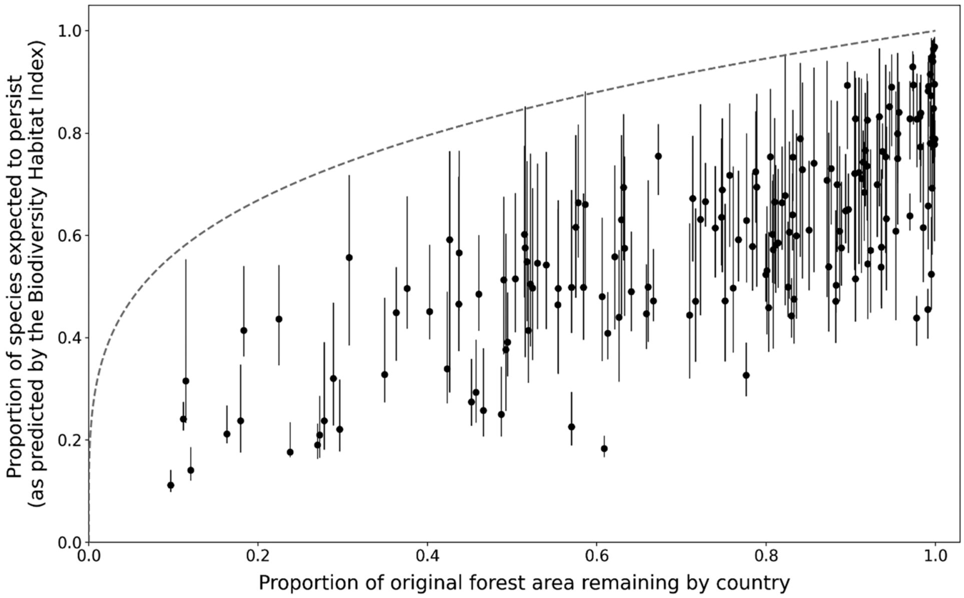

FIGURE 1 Relationship between the proportion of original forest remaining and the proportion of forest-associated plant species expected to persist (i.e., avoid extinction) over the long term in each of the world's forest-supporting countries. Results are presented only for countries within which forests originally covered a total area of more than 50 km^2. The broken-line curve depicts the level of species persistence expected as a simple species-area-based function of the proportion of original forest extent remaining in a country (assuming a species-area exponent of 0.25). Each of the black symbols depicts the proportion of species expected to persist within a given country as estimated by the Biodiversity Habitat Index (BHI) derived from 2019 mapping of the Forest Landscape Integrity Index (FLII). Each of the vertical lines depicts the 5th and 95th percentiles of the distribution of BHI values for all originally forested 30-arcsec cells within a country (i.e., predictions of the proportion of species originally associated with a given cell that are expected to persist anywhere in the country).

supporting countries, the proportion of forest-associated plant species expected to persist over the long term, at two policy-relevant spatial scales: (1) for each 30-arcsec grid-cell in the country of interest, the proportion of species originally associated with that cell that are predicted to persist anywhere in the country (i.e., avoid extinction at national level); and (2) for the country as a single unit, the proportion of species originally associated with that country which are predicted to persist anywhere in the country. To allow these country-level results for our BHI-based indicator to be compared directly with those based purely on a measure of ecosystem extent (i.e., GBF headline indicator A.2), we translated the extent of forest in each country into a prediction of the proportion of forest-associated plant species expected to persist as a standard species-area-based function of the proportion of that country's original forest extent (prior to human modification) remaining.

Further details of the data and analytical methods employed in this study are provided in Supporting Information.

3 | RESULTS AND DISCUSSION

Three important findings emerge from our comparative analysis. First, the proportion of forest-associated plant species predicted to persist in each country is, on average, greatly reduced once the added effects of ecosystem integrity and connectivity, and of variation in community composition, are considered alongside that of change in ecosystem extent, with this mean proportion dropping from 0.911 to 0.593 (Figure 1, Table S1). When translated into predictions of the proportion of species therefore committed to extinction in each country, the results for our BHI-based indicator suggest an average (per country) extinction level 4.54 times higher than that based on ecosystem extent alone. Second, integrating the effects of ecosystem integrity, connectivity, and compositional variation has a greater impact on predicted levels of persistence in some countries than in others (Figures 1 and 2). These levels are therefore not very strongly correlated with those predicted through application of the species–area relationship to the proportion of original forest extent remaining in each country (Pearson correlation = 0.763; R^2 = 0.582). These two findings, in combination, suggest that considerable caution needs to be exercised in employing a headline indicator based solely on ecosystem extent to monitor progress by CBD Parties toward the achievement of the ecosystem-focused component of GBF Goal A, especially if this indicator is also expected to account for interlinkages with the species-focused component of this same goal.

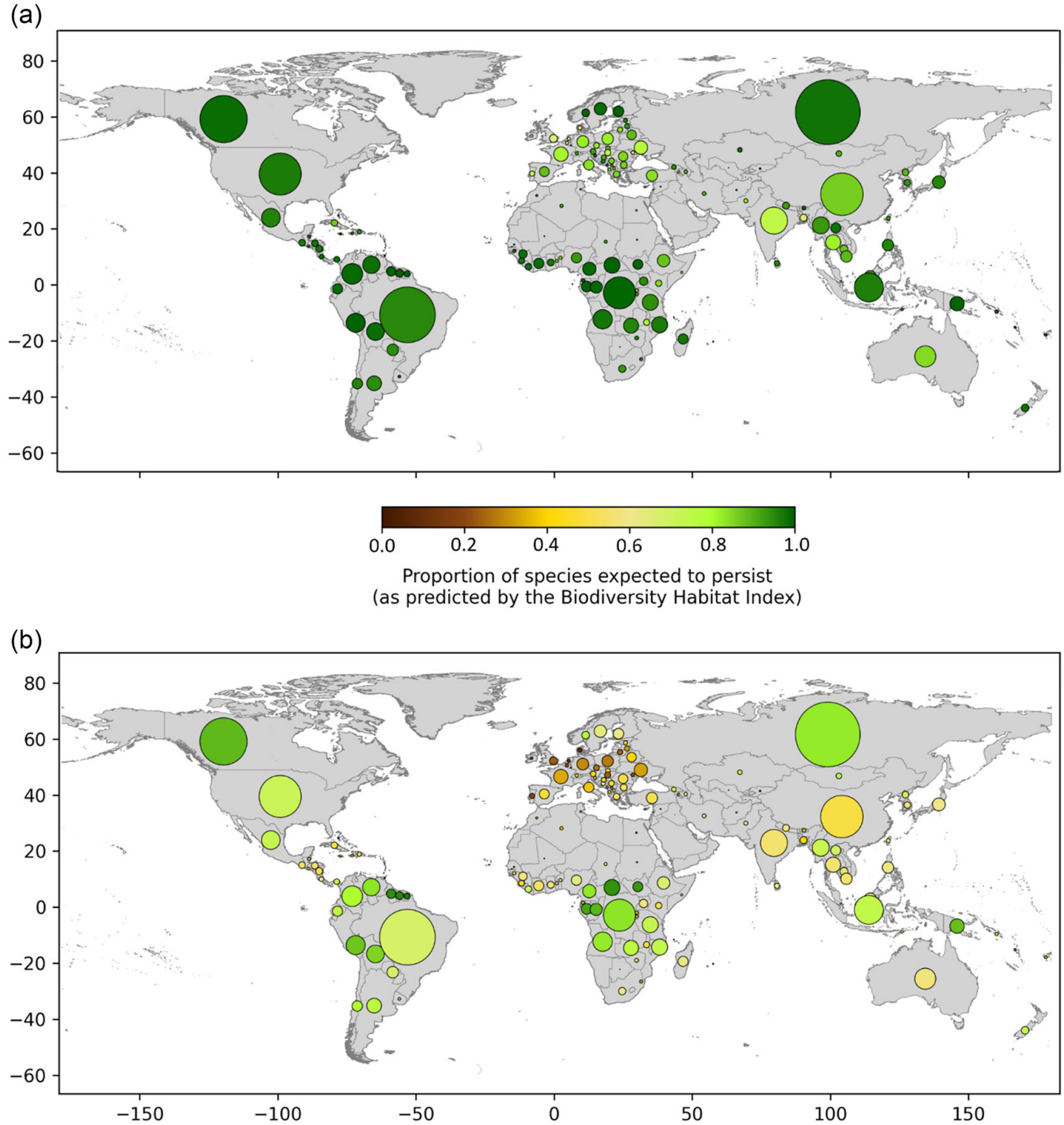

FIGURE 2 Proportion of forest-associated plant species expected to persist (i.e., avoid extinction) over the long term, in each of the world's forest-supporting countries. Results are presented only for countries within which forests originally covered a total area of more than 50 km^2. (a) The color of the circles indicates the proportion of species expected to persist as a simple species-area-based function of the proportion of forest remaining in each country (as for the broken-line curve in Figure 1). The size of the circles indicates the relative area originally covered by forest in each country. (b) As for panel (a), except now showing the proportion of species expected to persist as estimated by the Biodiversity Habitat Index derived from mapping of the Forest Landscape Integrity Index (as for the black symbols in Figure 1).

The third important finding relates more to the role indicators are likely to play in prioritizing where best to focus area-based actions to address shortfalls in the achievement of Goal A—including through spatial planning (GBF Target 1), ecosystem restoration (Target 2), and expansion of protected areas and other effective area-based conservation measures (Target 3) (CBD, 2022a). Such prioritization, if undertaken well, will often consider a range of relevant factors in addition to ecosystem extent. However, if an extent-focused indicator is employed as the sole foundation for assessing progress, there is a real risk that actions will be prioritized purely in terms of how much they increase the overall extent of ecosystems. In other words, any given amount of an action (e.g., an area of forest restored) will contribute equally to improving a country's score against this indicator, regardless of where the action is located within that country. The results for our BHI-based indicator suggest that the expected level of persistence of species diversity often varies dramatically between different parts of the same country (Figures 1 and 3). When the BHI is assessed at the scale of individual grid-cells—that is, predicting the proportion of species

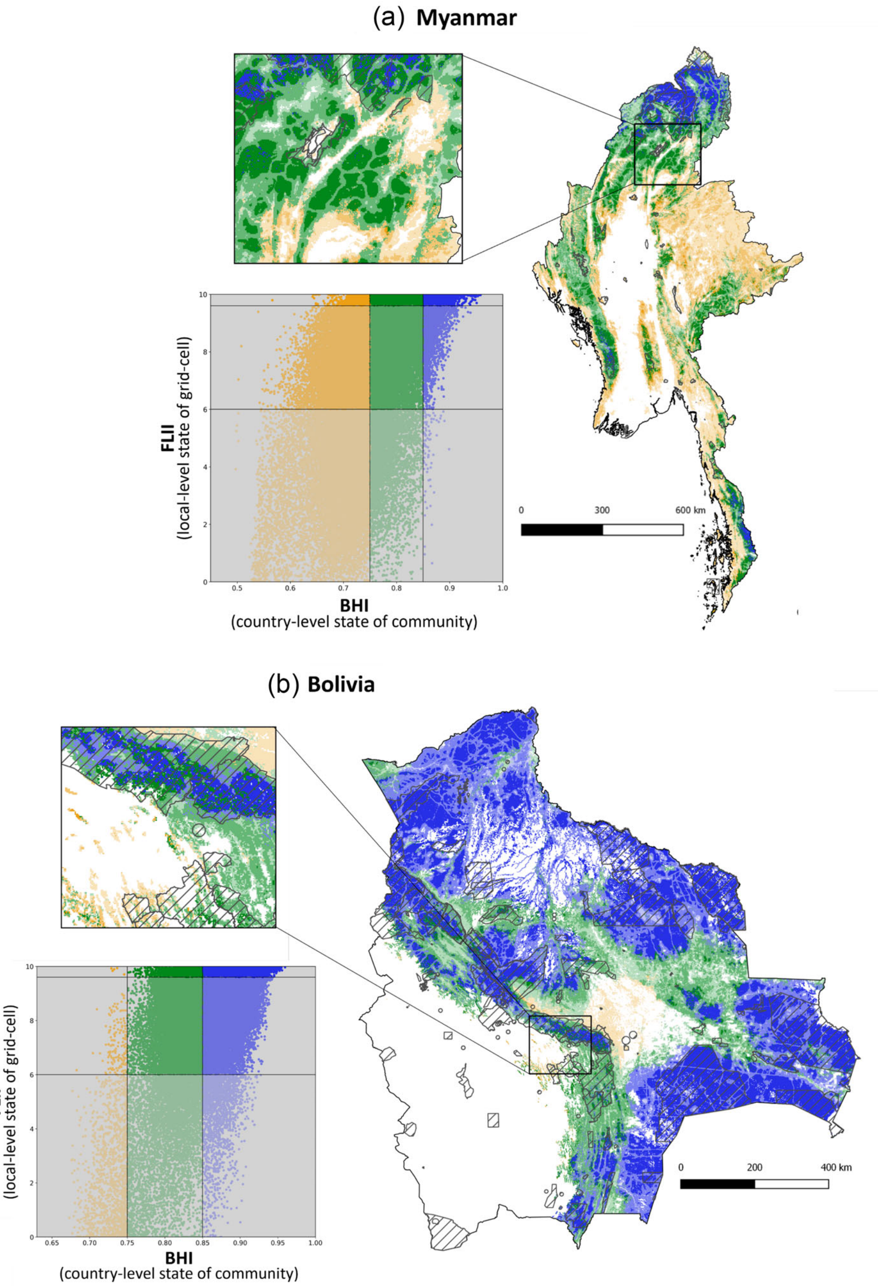

FIGURE 3 Fine-scale spatial variation in the Biodiversity Habitat Index (BHI) and the Forest Landscape Integrity Index (FLII) within two example countries: (a) Myanmar; (b) Bolivia. The two variables are mapped for all 30-arcsec cells containing forest in 2019 (i.e., cells with FLII > 0). Existing protected areas recorded in the World Database on Protected Areas are delineated with black hatching. Although both the BHI and the FLII are derived as continuous variables, each is here divided into three classes to aid in the interpretation of mapped patterns. Class cut-points for the BHI were set at 0.75 and 0.85, whereas those for the FLII were set at 6.0 and 9.6 (as proposed by Grantham, Duncan et al. (2020) for classifying low, medium, and high levels of the FLII). The scatterplot included for each country depicts the relationship between raw BHI and FLII values for a randomly selected 20% of the cells containing forest in 2019. Each symbol in this plot is colored according to which of the three classes of BHI and three classes of FLII the corresponding cell falls within. The colors used to depict class combinations in the scatterplot are the same as those used for the map. The BHI estimates, for each cell, the proportion of species originally associated with that cell which are predicted to persist anywhere in the country of interest, given the present state of forests across that country. It therefore indicates the relative need for action across different types (communities) of forest occupying different environments within the country. The FLII is instead a measure of the local state of forest within the cell itself and therefore indicates the contribution that different types of action within that cell (e.g., protection or restoration) might make to promoting the persistence of species originally associated with the cell.

originally associated with a given cell expected to persist anywhere in the country—the level of extinction predicted for the 5th percentile of BHI values within a country is, on average, 2.61 times higher than that for the 95th percentile of BHI values within that country (Figure 1, Table S1). This result confirms that past reduction in the extent and integrity of natural ecosystems is distributed neither uniformly nor randomly within most countries but is instead biased toward particular environments supporting particular assemblages of a country's species (Allnutt et al., 2008; Beresford et al., 2018; Liu & Slik, 2014; Simmonds et al., 2017). The contribution that a given amount of an area-based action will make to achieving biodiversity outcomes under Goal A will therefore depend greatly on where that action is located within the country concerned (Figure 3).

Further to this finding, the distribution of BHI values for individual grid-cells within a country tends to be only very weakly correlated with the distribution of FLII values for those same cells (Figure 3). This is because the BHI of any given cell is not simply a function of the condition or integrity of forest within that particular cell but is instead a function of the condition of all cells predicted to have once supported a similar composition of species to the cell of interest. When the BHI and FLII values of individual cells are plotted against each other—as we have done for two example countries, Myanmar and Bolivia, in Figure 3—it is clear that cells with the same FLII value can exhibit a wide range of BHI values. This suggests that the FLII alone, or indeed any other metric of ecosystem condition or integrity at a local cell-by-cell level, is unlikely to serve effectively as a basis for prioritizing actions, unless such data are coupled with information on the spatial distribution of species or ecological communities across the region or country of interest (Grantham, Shapiro et al., 2020; Mokany et al., 2020), as is achieved here through the derivation of the BHI.

4 | CONCLUSION

The clear conclusion to be drawn from our comparative analysis is that monitoring change in ecosystem extent alone is likely to fall well short in capturing the overall scope of the ecosystem-focused component of Goal A. Assessment of ecosystem extent, as addressed by GBF headline indicator A.2, is of critical importance to any effort to monitor the changing state of ecosystems. However, to effectively monitor progress toward the achievement of the ecosystem-focused component of Goal A and plan further area-based actions to address shortfalls in this achievement, this indicator needs to be augmented by the appropriate use of additional indicators addressing the other key dimensions of ecosystem change referenced in the definition of Goal A—that is, integrity, connectivity, and resilience.

As we noted at the outset, these other dimensions, together with ecosystem extent, are addressed by the methodology underpinning the Red List of Ecosystems—the other headline indicator identified for monitoring progress in relation to the ecosystem-focused component of Goal A (CBD, 2022c). Increased effort therefore needs to be directed to filling the sizeable gaps that currently exist in the coverage of ecosystem types and countries by Red List of Ecosystems assessments (Nicholson et al., 2021).

In parallel with this effort, there is potential to make stronger use of indicators from the component and complementary indicator sets (CBD, 2022c), which already combine consideration of both ecosystem extent and integrity in assessing biodiversity change globally. For example, the BHI we have employed here has already been generated across all terrestrial biomes globally (both forest and non-forest) based on a habitat-condition time series derived from downscaled land-use mapping (Hoskins et al., 2020; UNEP WCMC, 2024). Considerable potential now exists for the level of rigor with which we have rederived the BHI for forests in our current study to be extended progressively to other non-forest biomes once mapping of ecosystem integrity underway across these systems reaches a similar standard to that of the forest-focused FLII (Beyer et al., 2020).

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DATA AVAILABILITY STATEMENT

Links to all input datasets used to derive the forest extent and integrity layers, and the vascular plant beta-diversity models, employed in this study are provided in Grantham, Duncan et al. (2020) and Hoskins et al. (2020). Data for the Forest Landscape Integrity Index can be accessed at https://www.forestintegrity.com/. All 30-arcsecond grid-resolution results for the Biodiversity Habitat Index generated by this study can be accessed at https://zenodo.org/records/13251276.

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SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

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