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Subnational biodiversity reporting metrics for mountain ecosystems

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Biodiversity indicators are used to assess progress towards conservation and sustainability goals. However, the spatial scales, methods and assumptions of the underlying reporting metrics can affect the provided information. Using mountain ecosystems as an example, we compare biodiversity protection at subnational scale using the site-based approach of the 2030 Agenda for Sustainable Development (SDG indicator 15.4.1) with an area-based approach compatible with the targets of the Kunming–Montreal Global Biodiversity Framework.

Sustainable development and nature conservation take place in heterogeneous socioeconomic, environmental and policy contexts characterized by unevenly distributed biodiversity[1]. Hence, conservation-related indicator maps calculated at the level of entire countries provide high-level overviews critical for raising awareness but often provide little information about the management actions taken or needed at relevant scales[2,3]. Overcoming these limitations requires subnational maps based on steadily improving spatial data layers that account for the uneven distribution of biodiversity within countries. Such maps enable the assignment of responsibilities between parties and among conservation actors, reveal the need for complementarity in governance and action within and across state boundaries, and help ensure progress towards conservation and the Sustainable Development Goals (SDGs) while 'leaving no one behind', a core value and promise of the United Nations (UN) 2030 Agenda for Sustainable Development[4]. However, although available at increasing resolution, spatial data layers are not always used for breaking down indicators from the national scale to the scale at which policymaking, planning and conservation happen.

Mountains are a quintessential example in this context. They host exceptionally rich and functionally important biodiversity[5,6]; differ in their species' diversity, spatial distribution and levels of endemism across latitudinal, longitudinal and elevational gradients[5–7]; and represent distinct social–ecological systems and landscape units[8] that fall under different jurisdictions within and between countries. As such, they constitute pertinent conservation units and are acknowledged as a conservation priority[9] in the face of accelerating global change. Yet reporting on mountain biodiversity conservation in the context of the 2030 Agenda for Sustainable Development (SDG indicator 15.4.1, coverage by protected areas of important sites for mountain biodiversity[10]) is performed only at the scale of entire nations, regions or the world. This is the case despite the existence of mountain delineations that enable reporting on biodiversity protection at the level of mountain ranges and systems[8]. In this Brief Communication, we address this gap by applying our most recent mountain inventory[8] to generate spatially disaggregated annual maps of SDG indicator 15.4.1. By doing so, we use the mountain context as an example to illustrate the feasibility of spatially explicit reporting. Moreover, the reporting by means of SDG indicator 15.4.1 does not account for the extent of the Key Biodiversity Areas (KBAs, 'sites that contribute significantly to the global persistence of biodiversity'[11]) under protection, whereas the action-oriented global targets adopted under the Kunming–Montreal Global Biodiversity Framework[12] could be interpreted in terms of the total percentage of areas under protection. We therefore compare averaged site-level percentages protection (the currently used 'site-based approach') with area-based values that we calculate as the ratios between the protected fractions and the total extent of mountain KBAs ('area-based approach'), highlighting differences and complementarities. To enable the use of our findings by different scientific, management and policy groups, we maintain a web platform to explore and compare spatio-temporal trends in the indicator

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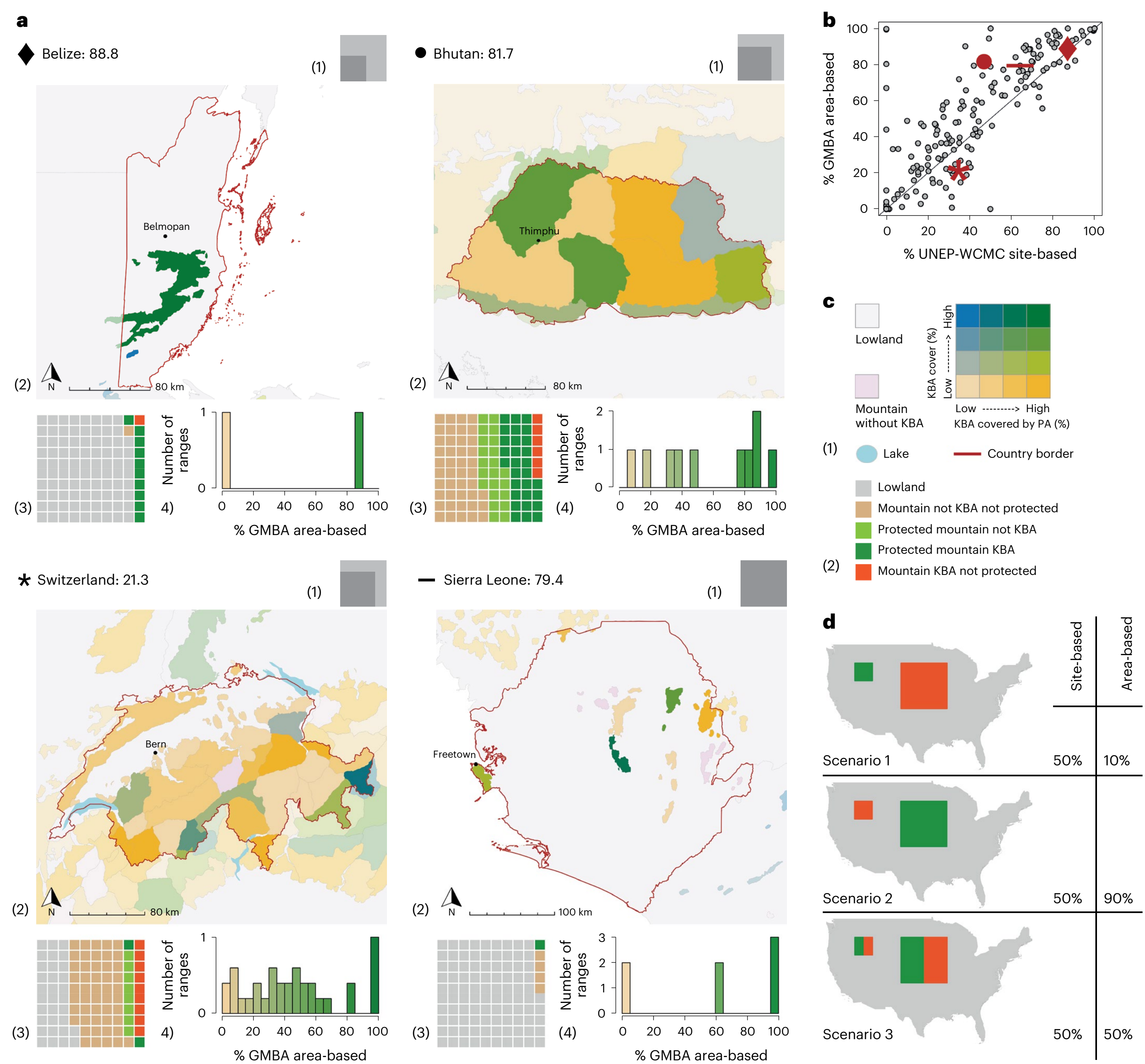

Fig. 1 | KBA coverage by PA. a, Area-based SDG indicator 15.4.1 for mountain ranges of Switzerland, Bhutan, Belize and Sierra Leone: (1) relative country size compared with the smallest; (2) bivariate map of KBA coverage by PA; (3) country area partitioning into lowland and mountains (1 square approximates 1%); (4) number of ranges per subnational indicator values (excludes ranges with no KBA). **b**, Comparison between area- and site-based calculations. Red symbols, countries in **a**; circles, other countries; diagonal, same value for both calculations (not considering a country's mountain area). **c**, (1) legend for **a** (2 and 4); (2) legend for **a** (3). **d**, Comparison between area- and site-based calculations for three scenarios of PA coverage of two KBAs differing in size (green, protected KBA; red, KBA not protected). For illustration purposes, site-based values are identical despite differences in the extent of protected KBA (Extended Data Fig. 2).

at different scales and according to different calculations (https://mountainbiodiversity.net/). Further, we provide one-page summaries for countries and mountain systems (Fig. 1; ref. 13) and the R code to replicate the results at mountain range level[14] as open access material.

The disaggregation of SDG indicator 15.4.1 (Fig. 1a) demonstrates that with protection levels of KBAs varying from 0 to 100% across mountain ranges within countries (for example, Bhutan or Switzerland; Supplementary Table 1 and Fig. 1a (2) and (4)), the information content of country-level indicators is limited. Disaggregated calculations reveal the spatial variability in biodiversity protection within and across countries that is concealed in unique country-level averages[15] and indicate where—and by how much—protection needs to increase. Our approach thus enables annual reporting at spatial scales relevant for policymaking, prioritization and management and contributes to improving the coherence of environmental policies for mountains across scales.

The disaggregation further reveals differences in how well countries protect their shares of transboundary mountain systems. In the European Alps, for example (Fig. 2), levels of protection are lower in Switzerland (~30%) than in neighbouring countries such as Italy (~70%) and Germany (>95%). Given that mountain ecosystems, species and most environmental threats do not stop at political boundaries, such

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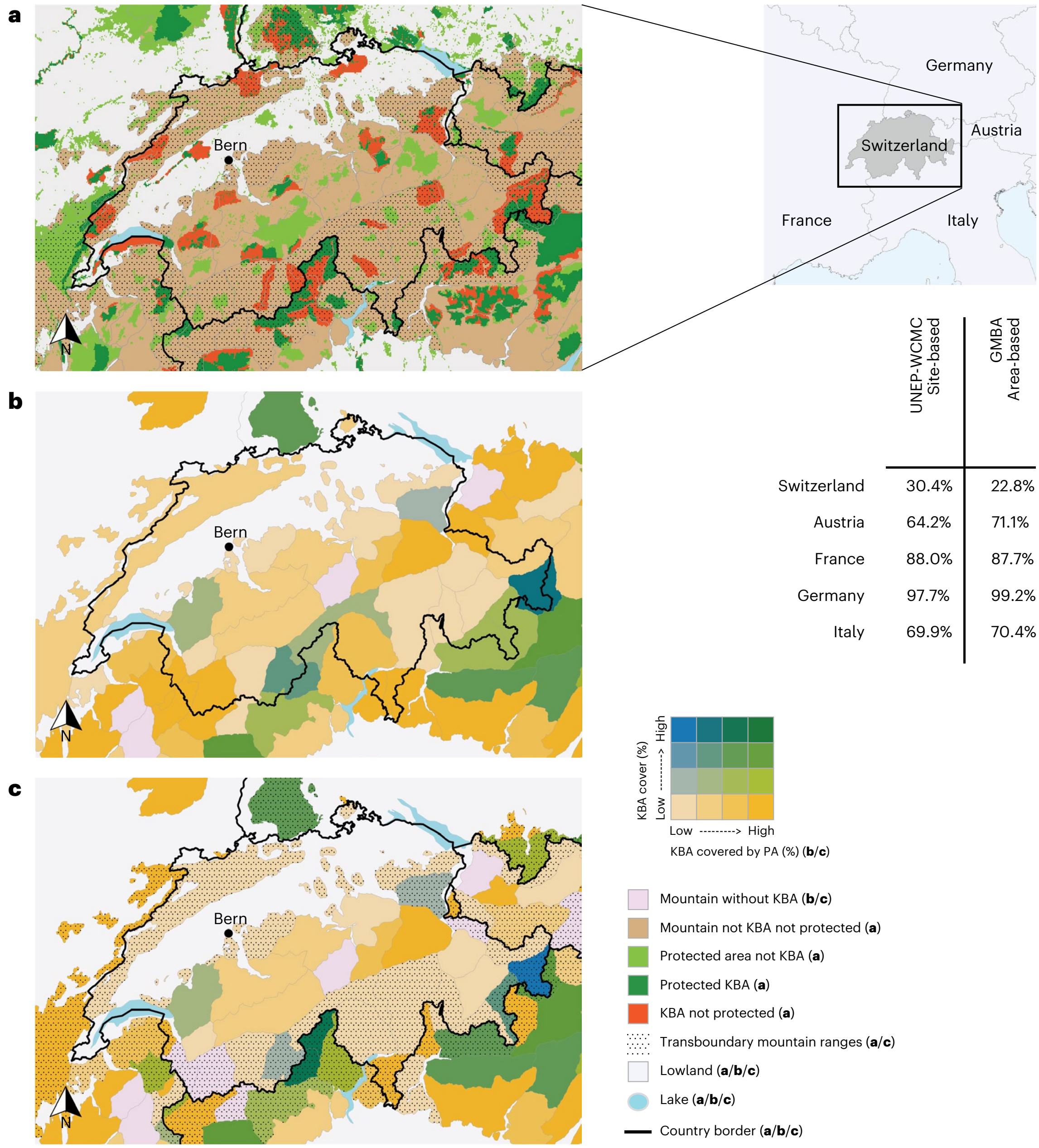

Fig. 2 | Transboundary protection of mountain biodiversity. a, KBA coverage by PA across transboundary ranges (dotted areas). Light green, PA not KBA; dark green, protected KBA; red, KBA not protected. Right: site-/area-based national value for Alpine countries neighbouring Switzerland. **b**,**c**, Bivariate map of KBA coverage by PA, disaggregated to the mountain range level (**b**) by country (**c**).

differences might compromise conservation efforts, in particular when countries have very unequal shares of mountain systems. Yet overall, transboundary protection objectives that do not depend on equally high levels of protection across involved countries might nevertheless be achieved. Our results therefore enable the informed assignment of responsibilities between parties and support the implementation of transboundary conservation as a process of international cooperation[16,17] to overcome the social, economic and environmental challenges faced by mountain biodiversity and its beneficiaries.

Comparing the site- and area-based approaches for calculating the levels of protection of mountain KBAs (Supplementary Table 1 and Extended Data Figs. 2 and 3) reveals differences between national-level SDG indicator 15.4.1 values (Fig. 1b). This is the case for nearly 90% of the countries (Supplementary Table 2), with an average difference of 13 percentage points. In more than 65% of these 190 countries, area-based indicator values are higher than site-based values. Within individual countries, differences in SDG indicator 15.4.1 values can be considerable. This is the case for the mountainous country of Bhutan, for example, with 35 percentage points in 2020 (47% and 82%, respectively). This highlights the importance and consequences of methodological choices and calls for caution in the choice of reporting metrics and for careful interpretation of computed values.

The current site-based approach calculates the average percentage coverage by PAs and other effective area-based conservation measures (OECMs) of all mountainous KBAs within a country[10]. The 'mountainous' classification is based on a minimum overlap of 5% between a KBA and terrain that is considered in mountains according to the mountain definition of the UN Environment Programme World Conservation Monitoring Centre (UNEP-WCMC)[18], which, as a result of its calculation, includes comparatively larger areas of flat and rolling terrain. This implies that mountainous KBAs can consist of sizeable portions of hills and lowlands, especially for very large KBAs. Further, according to the site-based calculation, PAs are intersected with entire KBAs and not only with their strictly mountainous fractions. Accordingly, the percentage PA for any given KBA is attributed to mountains even when the PA covers the lowland parts of the mountain KBA. Finally, the treatment of all KBAs as equal regardless of their size (Fig. 1d) helps account for the fact that smaller sites may be particularly effective for conservation, especially for range-restricted species[19]. However, this can also lead to inflated indicator values (Fig. 1d, scenario 1), in particular if the size distribution of KBAs is skewed towards smaller sites (Extended Data Figs. 2 and 3).

The area-based calculation sums the actual area of mountain terrain (sensu ref. 8) that intersects with KBAs and calculates what percentage of this terrain is protected. Accordingly, indicator values increase only with increasing area of protected mountain KBAs. By using a more conservative mountain definition that mostly excludes less-rugged hills and lowlands, and by defining mountain KBAs as the actual area of land that is both mountainous and important for biodiversity, the area-based method overcomes the issue of reporting on PA coverage of land that is not in fact in mountains. Area-based values thereby reflect efforts to protect areas of importance for the persistence of biodiversity that are both large and located strictly in mountains. However, in the presence of at least one large site benefiting from a high protection, overall values are likely to be high despite the possible existence of poorly protected smaller sites (Fig. 1d, scenario 2).

Currently, SDG indicator 15.4.1 quantifies the average percentage PA coverage of sites that are important for mountain biodiversity persistence and located (partly) in mountains[10]. The area-based calculation of SDG indicator 15.4.1 at the subnational level sheds a different and complementary light on mountain biodiversity protection and highlights areas within mountain regions in need of subnational to international conservation efforts. Disaggregation and area-based calculations do not resolve the known shortcomings of KBAs for reporting on biodiversity conservation[19,20]. However, they enable the quantification of progress towards the area-based action-oriented targets of the Kunming–Montreal Global Biodiversity Framework. Moreover, the methodological considerations also apply for other (non-KBA) designations of importance.

Our work on SDG indicator 15.4.1 highlights the need for transparency and caution with regard to the methods and assumptions underlying metrics for informing on sustainability and conservation. With our online resources, we offer tools to support science-based decision-making for complex mountain environments. We enable users to perform their own calculations and comparisons at the relevant scale, understand what indicators mean and conceal, compare different methods and assumptions, and explore time series across mountains. Our online resources support users across sectors and institutions in correctly interpreting the metrics on which decisions and management are based.

Methods

We calculated SDG indicator 15.4.1 following the official site-based methodology developed by Birdlife International (BLI; https://github.com/BirdLifeInternational/kba-overlap; refs. 10,21) and an area-based approach. We did so for entire countries (for example, France), mountain ranges (for example, European Alps) and their intersections (for example, French Alps), which are also the reporting units presented on the web platform.

Input data

Input data were (Supplementary Table 3 and Extended Data Fig. 1 (1)) (1) a prefiltered version of the World Database on Protected Areas (WDPA, Protected Planet[22]) received from BLI, (2) the World Database of KBAs[23], (3) UNEP-WCMC mountain KBA list (BLI based on the UNEP-WCMC mountain definition[18]) and (4) the Global Mountain Biodiversity Assessment Mountain Inventory v.2.0 (GMBA Inventory)[8]. The WDPA data excluded UNESCO Man and Biosphere Reserve sites (they may include unprotected buffer zones), sites with no corresponding polygons (precise PA borders are needed) and other effective area-based conservation measures (incomplete).

Selection and subsetting of mountainous KBAs

For the site-based approach, we selected all KBAs classified as mountainous on the basis of the UNEP-WCMC mountain KBA list and attributed each entirely to the GMBA Inventory mountain range with which it had the largest overlap. To follow the official methodology as closely as possible, we used the version of the GMBA Inventory that includes terrain identified as mountainous also by the UNEP-WCMC definition (GMBA Inventory 'Broad'). For the area-based approach, we intersected the KBAs with the mountain ranges of the GMBA Inventory to obtain a layer of mountain KBAs. In this case, we used a version of the GMBA Inventory that encompasses mountain terrain identified solely by the GMBA mountain definition (GMBA Inventory 'Standard').

Overlap with PAs

For both approaches, we calculated the percentage PA coverage for each KBA (the value for SDG indicator 15.4.1; Extended Data Fig. 1 (4) and (5)). We first computed the area of intersection between each mountain KBA (Extended Data Fig. 1 (3)) and the overlapping PA with the earliest designation year (Extended Data Fig. 1 (4)). For each subsequent year, we calculated additional intersections and summed the areas. We did so as long as there were more recently designated PAs that intersected with the mountain KBA or until the percentage protection of the KBA had reached ≥98%. Missing designation years were assigned a year randomly either within the range of all the designation years for all PAs in that country or after 1986 if all designation years were missing. See Supplementary Tables 4–6 for output file information of absolute and percentage PA coverage of KBAs.

Aggregation and final output

We expressed the results of both methods as annual cumulative coverage and aggregated these data to countries, mountain ranges and the intersections between ranges and countries (Supplementary Tables 7 and 8 and Extended Data Fig. 1 (6)). Site-based aggregations represent the average of the protected percentage of KBA sites within each reporting unit (countries, mountain ranges and their intersections; Extended Data Fig. 2a). The country-level results of the site-based method paralleled the official indicator and were used to validate our R code. Area-based aggregations represent the total protected KBA area divided by the total KBA area at each reporting unit (Extended Data Fig. 2b).

Reporting summary

Further information on research design is available in the Nature Portfolio Reporting Summary linked to this article.

Data availability

The most recent version of the World Database on Protected Areas (WDPA) can be accessed through the website: https://www.protectedplanet.net/en/thematic-areas/wdpa?tab=WDPA. Data on KBAs can be accessed by request via this form: https://www.keybiodiversityareas.org/kba-data/request. The GMBA mountain inventory is accessible online: https://www.earthenv.org/mountains, https://doi.org/10.48601/earthenv-t9k2-1407. Data generated to support the results and conclusions of this study are available at https://github.com/GMBA-biodiversity/SDG15.4.1_Calculator/tree/master/results. Metadata associated with these data are available at https://github.com/GMBA-biodiversity/SDG15.4.1_Calculator/blob/master/Metadata.xlsx.

Code availability

The R scripts used to execute and report on the analyses in this paper can be found at https://github.com/GMBA-biodiversity/SDG15.4.1_Calculator.

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Author contributions

D.U., J.G. and M.A.S. conceptualized the project. A.L., J.G., M.A.S and D.U. developed the methodology. A.L. curated data and wrote the code. A.L. and M.A.S. completed the formal analysis. A.L. and D.U. wrote the original manuscript draft. A.L., J.G., M.A.S., N.S.D., M.F. and D.U. contributed to reviewing and editing the manuscript. A.L., J.G. and M.A.S. created manuscript visualizations. J.G. created the one-page summaries. K.L.S., J.N. and D.S. created the online visualization. D.U. secured funding for the project.

Competing interests

The authors declare no competing interests.

Additional information

Extended data is available for this paper at https://doi.org/10.1038/s41893-023-01232-3.

Supplementary information The online version contains supplementary material available at https://doi.org/10.1038/s41893-023-01232-3.

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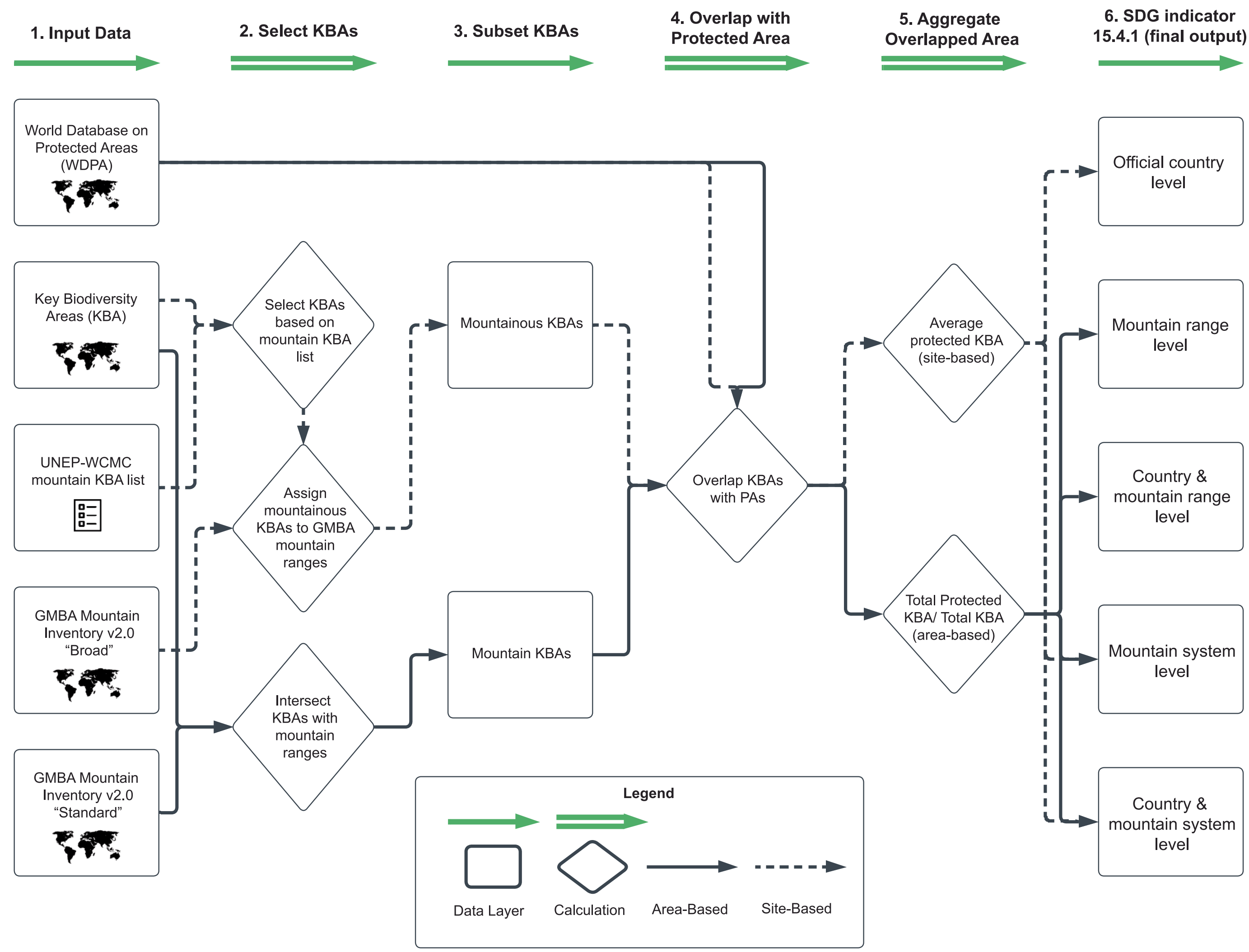

Extended Data Fig. 1 | Workflow for site- and area-based calculations. Squares or solid green lines: data layers. Diamonds or double green lines: pivotal calculation decisions. Dotted black arrows: site-based calculation method that follows the official methodology for calculating the SDG indicator 15.4.1. Solid arrows: area-based calculations.

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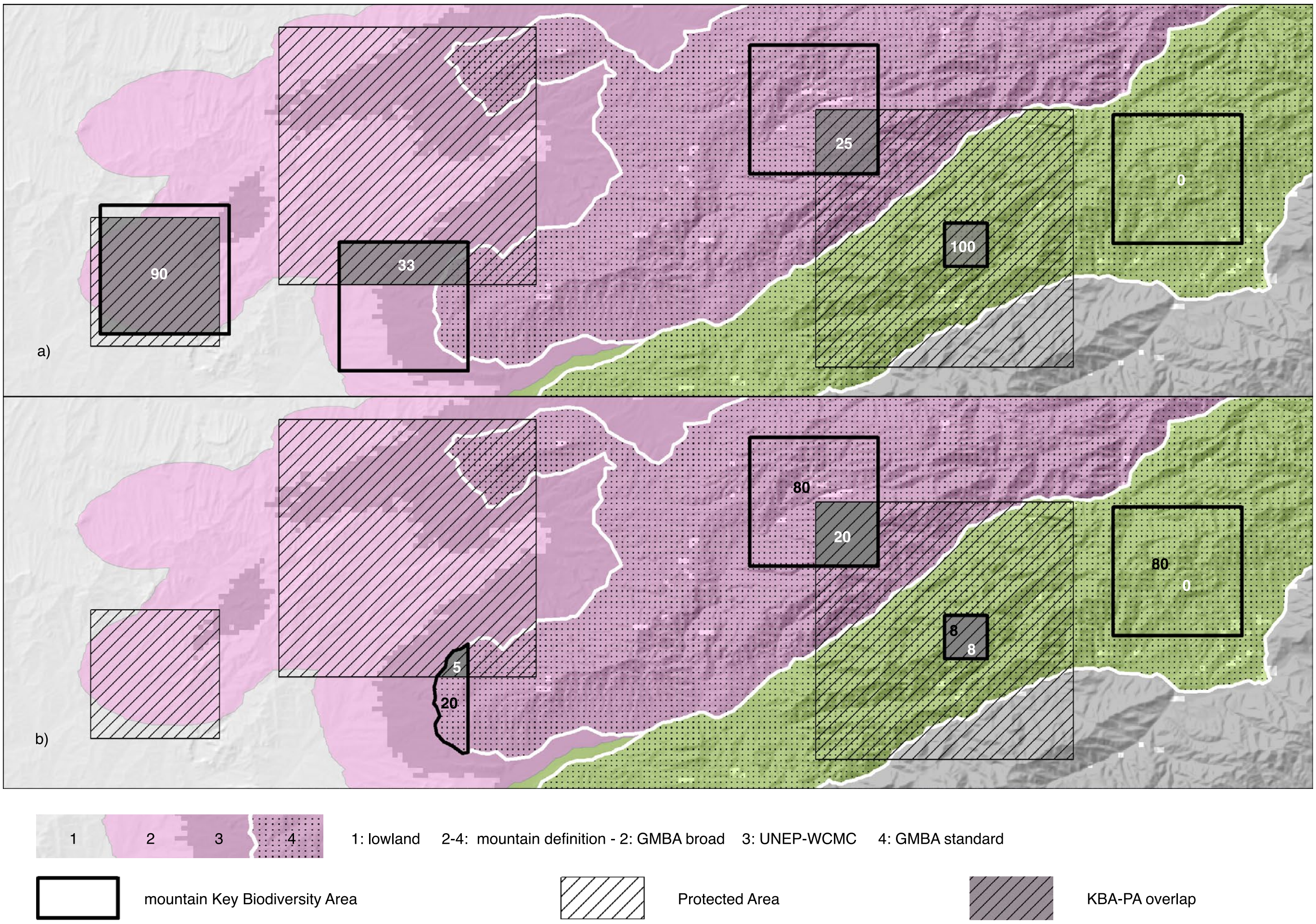

a)	Calculation: mean of the overlaps XX (in %)	Indicator value
Overall	(90% + 33% + 25% + 100% + 0%) / 5	49.6%
Range 1	(90% + 33% + 25%) / 3	49.3%
Range 2	(100% + 0%) / 2	50.0%

b)	Calculation: sum of the overlaps XX (in ha) divided by sum of the KBAs XX (in ha) times 100	Indicator value
Overall	(5 ha + 20 ha + 8 ha + 0 ha) / (20 ha + 80 ha + 8 ha + 80 ha) * 100	17.5%
Range 1	(5 ha + 20 ha) / (20 ha + 80 ha) * 100	25.0%
Range 2	(8 ha + 0 ha) / (8 ha + 80 ha) * 100	9.1%

Extended Data Fig. 2 | Method-dependence of assessing the overlap between KBAs and Pas. a) site-based calculation; **b**) area-based calculation (See Supplementary Information for more details).

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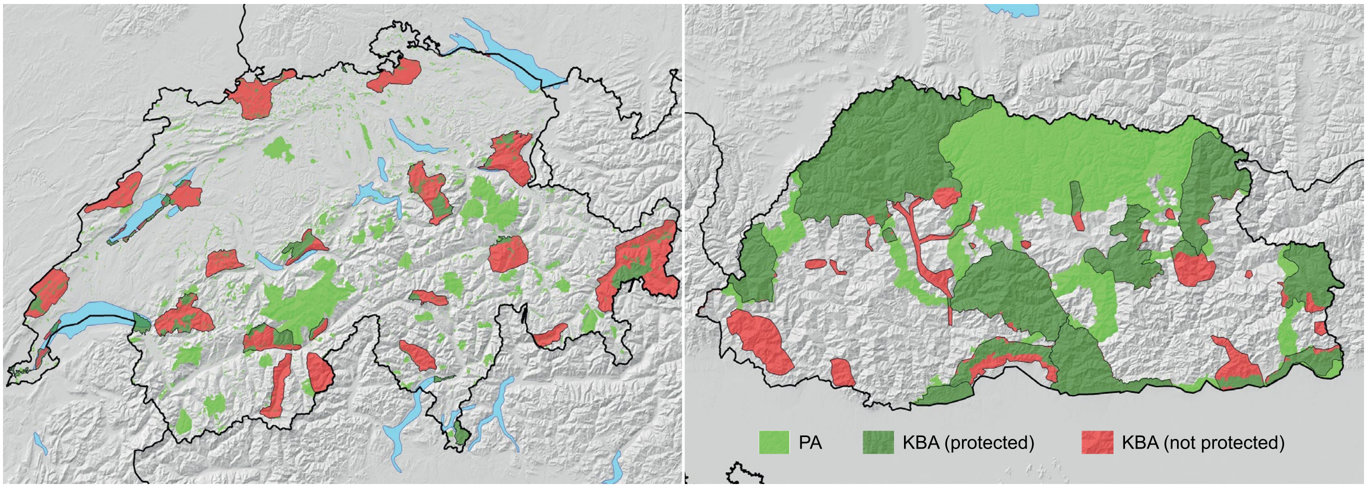

	Switzerland	Bhutan	Difference (percentage points)
Site-based	35%	47%	12
Area-based	21%	82%	61

Extended Data Fig. 3 | Mountain biodiversity protection in Switzerland and Bhutan. Mountain biodiversity protection in Switzerland (left) and Bhutan (right) and comparison between site-based and area-based national-level indicator estimates for SDG indicator 15.4.1 in 2020. Light green: PA not KBA; dark green: protected KBA; red: KBA not protected.

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Reporting Summary

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n/a	Confirmed	
☐	☒	The exact sample size (*n*) for each experimental group/condition, given as a discrete number and unit of measurement
☒	☐	A statement on whether measurements were taken from distinct samples or whether the same sample was measured repeatedly
☒	☐	The statistical test(s) used AND whether they are one- or two-sided *Only common tests should be described solely by name; describe more complex techniques in the Methods section.*
☒	☐	A description of all covariates tested
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☒	☐	For null hypothesis testing, the test statistic (e.g. *F*, *t*, *r*) with confidence intervals, effect sizes, degrees of freedom and *P* value noted *Give P values as exact values whenever suitable.*
☒	☐	For Bayesian analysis, information on the choice of priors and Markov chain Monte Carlo settings
☒	☐	For hierarchical and complex designs, identification of the appropriate level for tests and full reporting of outcomes
☒	☐	Estimates of effect sizes (e.g. Cohen's *d*, Pearson's *r*), indicating how they were calculated

Our web collection on statistics for biologists contains articles on many of the points above.

Software and code

Policy information about availability of computer code

Data collection	No software was used for data collection.
Data analysis	The R scripts used to execute and report on the analyses in this paper can be found at https://github.com/GMBA-biodiversity/SDG15.4.1_Calculator

For manuscripts utilizing custom algorithms or software that are central to the research but not yet described in published literature, software must be made available to editors and reviewers. We strongly encourage code deposition in a community repository (e.g. GitHub). See the Nature Portfolio guidelines for submitting code & software for further information.

Data

Policy information about availability of data

All manuscripts must include a data availability statement. This statement should provide the following information, where applicable:

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The most recent version of world database on protected areas (WDPA) can be accessed through the website: https://www.protectedplanet.net/en/thematic-areas/wdpa?tab=WDPA. Data on key biodiversity areas (KBA) can be accessed by request via this form: https://www.keybiodiversityareas.org/kba-data/request. The GMBA mountain inventory is accessible online: https://www.earthenv.org/mountains, https://doi.org/10.48601/earthenv-t9k2-1407. Data generated to support the results and conclusions of this study are available at: https://github.com/GMBA-biodiversity/SDG15.4.1_Calculator/tree/master/results. Metadata associated with these data are available at: https://github.com/GMBA-biodiversity/SDG15.4.1_Calculator/blob/master/Metadata.xlsx.

Human research participants

Policy information about studies involving human research participants and Sex and Gender in Research.

Reporting on sex and gender	Not applicable to this study
Population characteristics	Not applicable to this study
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Ethics oversight	Not applicable to this study

Note that full information on the approval of the study protocol must also be provided in the manuscript.

Field-specific reporting

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Ecological, evolutionary & environmental sciences study design

All studies must disclose on these points even when the disclosure is negative.

Study description	Recalculation of SDG 15.4.1, and introduction of alternative methods for calculating, summarizing, and aggregating data. We report on the general results and comparison of the methods.
Research sample	Global analysis of all mountainous key biodiversity areas .
Sampling strategy	Not applicable to this study.
Data collection	Data were all obtained externally
Timing and spatial scale	For WDPA and KBA data, the 2020 datasets were used for this analysis. We do not include any protected areas designated or key biodiversity areas identified after 2020. The analysis was completed on a global, terrestrial scale, however final reporting was completed only on mountainous regions.
Data exclusions	The WDPA shapefile data utilized included only polygons, sites whose status was one of Adopted', 'Designated', 'Inscribed', or 'Established'. Excluded from the analysis were UNESCO-MAB protected areas, and protected areas that were saved as points rather than polygons. This strategy mirrors that of the methodology reported for Sustainable Development Goal 15.4.1. Calculations for the area-based coverage excluded KBAs that were deemed to be duplicates (based on >= 98% overlap)
Reproducibility	Calculations are reproducible utilizing published code and data on github, in addition to the larger datasets mentions in the data availability statement.
Randomization	Not applicable to this study.
Blinding	Not applicable to this study.

Did the study involve field work? ☐ Yes ☒ No

Reporting for specific materials, systems and methods

We require information from authors about some types of materials, experimental systems and methods used in many studies. Here, indicate whether each material, system or method listed is relevant to your study. If you are not sure if a list item applies to your research, read the appropriate section before selecting a response.

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☒	☐	Palaeontology and archaeology
☒	☐	Animals and other organisms
☒	☐	Clinical data
☒	☐	Dual use research of concern

Methods

n/a	Involved in the study	
☒	☐	ChIP-seq
☒	☐	Flow cytometry
☒	☐	MRI-based neuroimaging