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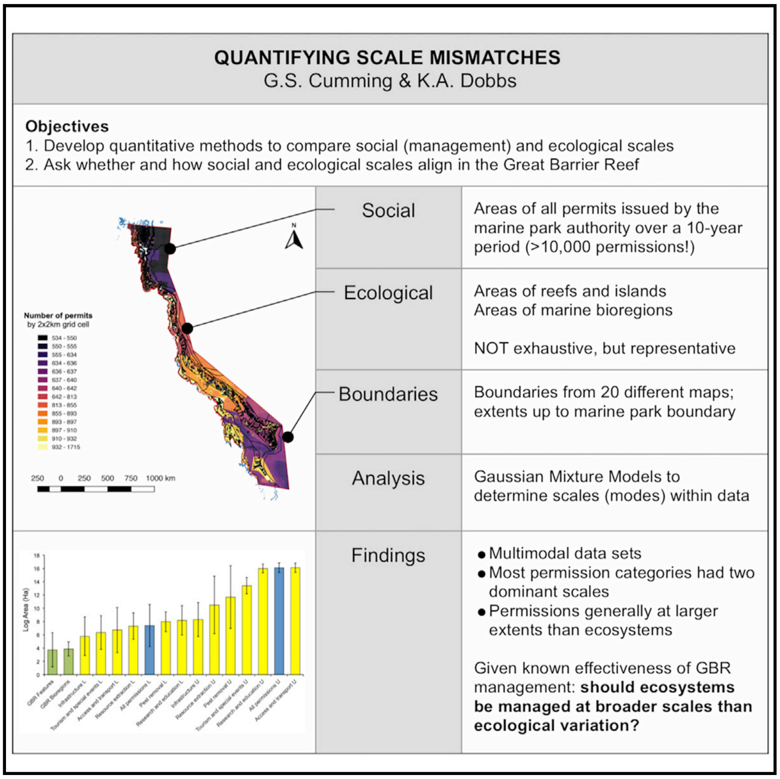
Quantifying Social-Ecological Scale Mismatches Suggests People Should Be Managed at Broader Scales Than Ecosystems

Graphical Abstract



QUANTIFYING SCALE MISMATCHES
G.S. Cumming & K.A. Dobbs

Objectives
1. Develop quantitative methods to compare social (management) and ecological scales
2. Ask whether and how social and ecological scales align in the Great Barrier Reef

Social	Areas of all permits issued by the marine park authority over a 10-year period (>10,000 permissions!)
Ecological	Areas of reefs and islands Areas of marine bioregions NOT exhaustive, but representative
Boundaries	Boundaries from 20 different maps; extents up to marine park boundary
Analysis	Gaussian Mixture Models to determine scales (modes) within data
Findings	• Multimodal data sets • Most permission categories had two dominant scales • Permissions generally at larger extents than ecosystems Given known effectiveness of GBR management: **should ecosystems be managed at broader scales than ecological variation?**

Highlights

- Mapping permits and ecological data allowed us to compare social and ecological scales
- Dominant extents of institutions and ecological systems occurred across multiple scales
- Scales of permissions were typically bimodal and larger than ecological scales
- We propose that effective management is at broader scales than ecological variation

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In Brief

Mapping permits and ecological data across the Great Barrier Reef Marine Park allowed us to quantify and rigorously compare interacting social and ecological scales. Institutions (permits) and ecological systems both varied at multiple scales. The scales of permissions were typically bimodal and larger than ecological scales. Thus, we propose that effective management may have to occur at broader scales than ecological variation. Further comparable examples are needed for establishing the generality of this proposition.

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Quantifying Social-Ecological Scale Mismatches Suggests People Should Be Managed at Broader Scales Than Ecosystems

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SCIENCE FOR SOCIETY Sustainable management of natural resources depends on effective, scale-appropriate monitoring and responses by managers. Broad-scale problems, for example, can be solved only by broad-scale solutions. By measuring and directly comparing the scales of management and ecological variation, our paper demonstrates an application of a rigorous approach to the assessment of how social and ecological scales align within a specific case study. For the Great Barrier Reef Marine Park, our results show that management occurs across a much wider range of scales than the scales of reefs, islands, and marine bioregions. This finding suggests that managers and resource users may benefit from being able to select focal points for action from within a broader range of possible action locations. Establishing the generality of our findings will, however, depend on additional comparisons from other social-ecological systems, including some for which management is dysfunctional.

SUMMARY

The management of natural resources creates feedbacks between ecosystems and societies, both of which exist at characteristic scales. Theory predicts that sustainability is higher when governance and management scales align with scales of ecological heterogeneity. We analyzed the areas of institutions (10,030 permissions from 7,478 permits in the Great Barrier Reef Marine Park, 2007–2017) and compared these with the areas of reef features and non-reef marine bioregions. Permission extents were bimodal; 72% were fine scale (median 16.5 km^2), and 28% were broad scale (median 99,193 km^2). Biophysical data were unimodal and at significantly smaller scales than permissions. Different permission scales for different activities indicated adaptability within the permitting system. Our analysis demonstrates a new approach to quantifying scale mismatches. It suggests that discrete institutional scales exist but differ from ecological scales and that rules at broader scales than the managed resource may allow greater adaptation and responsiveness by human users than rules at the same scales.

INTRODUCTION

Most management and policy approaches for ecosystems seek to ensure a consistent and sustainable flow of benefits to people, together with a minimization of ecological degradation.[1] Ecological change triggers human behavioral or institutional responses and vice versa, leading to the linkage of human societies and ecosystems as social-ecological systems.[2] As people interact with ecosystems, they undertake management actions at different scales to try to improve or retain key system elements and relationships (e.g., endangered species and pollination), to remove or limit harmful influences (e.g., invasive species or pathogens), or to regulate human use (e.g., fishing and tourism). It has been proposed that understanding the scales of human management interventions and their alignment (or lack of it) with the scales at which ecological patterns (e.g., stand size, coral reef area, and flood duration) and processes (e.g., dispersal, predation, and regeneration) occur is of central importance for the sustainable management of natural resources.[3–5]

Mismatches between social and ecological scales are thought to cause environmental, social, and/or economic problems.[6,7] More formally, scale mismatches occur "when the scale of

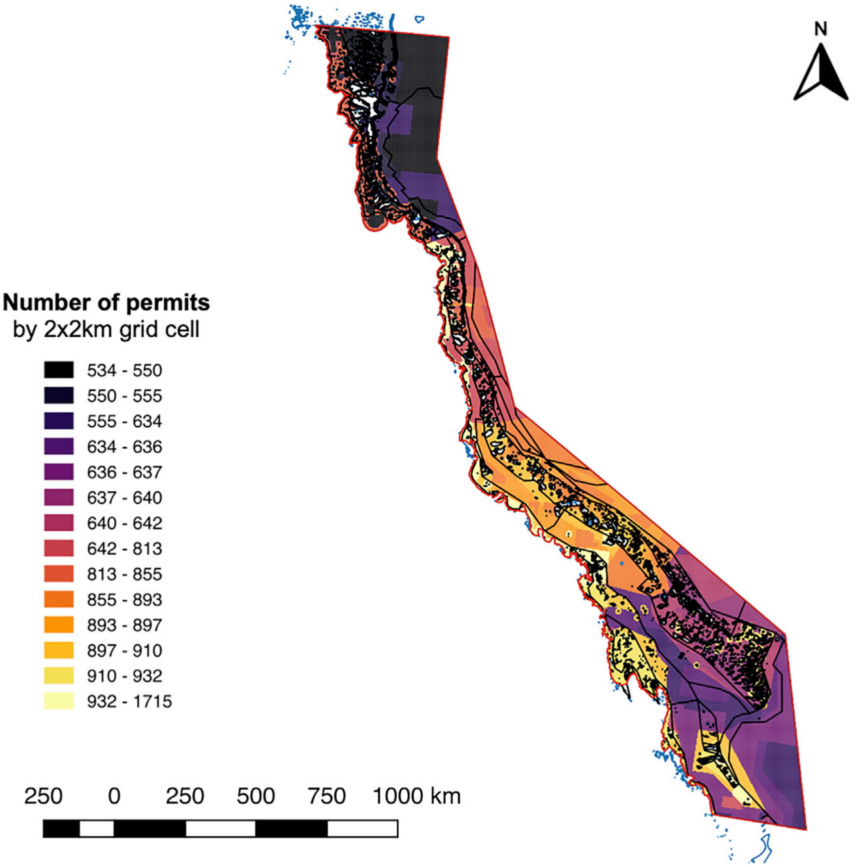

Figure 1. Map of the Great Barrier Reef Marine Park and the Northeast Coast of Australia

Colors indicate park boundary (red), numbers of permits per 2 × 2 km grid cell (shading), boundaries of marine bioregions (black), reefs and islands (white).

environmental variation and the scale of the social organization responsible for management are aligned in such a way that one or more functions of the social-ecological system are disrupted, inefficiencies occur, and/or important components of the system are lost."[8] Social-ecological scale mismatches may be spatial, temporal, or functional. Although there have been attempts to measure ecological scales and relate these to governance and management, few studies have rigorously defined, quantified, or explored the relationships between the different scales of both ecological variation and human management that co-occur within social-ecological systems.[9,10] Despite innovative attempts to formalize scale-mismatch concepts in emerging fields, such as using network analysis to understand social-ecological alignment in conservation planning,[11] most published research still reflects the focus of classic ecosystem management on harvested populations (e.g., fish and forests) and biophysical processes, such as fire and herbivory.[12,13] Detailed, empirical case studies from a diverse range of systems, including spatial analyses of human actions and institutions, are needed to more rigorously test, refine, and reflect on the core ideas that motivate research on scale mismatches.

To address this need, we used permit data from the iconic Great Barrier Reef Marine Park (GBRMP), situated off the northeast coast of Australia, as a test case (Figure 1). We tested two central but largely unrecognized and unexplored premises that are common in analyses of scale mismatches: (1) The premise of discrete institutional scales. Specifically, what were the scale(s) of permitting within the GBRMP and were permits clustered at particular scales or spread over a smooth continuum? (2) The premise that institutional scales are driven by biophysical scales. Specifically, did the areal scale(s) of permitting either match directly or correspond in an obvious way to the scales of individual coral reefs and other marine habitats? We also asked whether there were obvious differences in median extent between permits issued for the six basic kinds of activity (as described in the Experimental Procedures) for which permits are issued in the GBRMP. Rather than focusing on single cases, in which a single scale of ecological variation is considered in relation to a single scale of governance (e.g., cooperation between farmers at a multi-farm scale to control pests),[14] we adopted a population-level approach, in which we relate a large number of individual institutional areal scales to a large number of ecological areal scales within the same boundary. Our results show that the areal scales of permitting were generally larger than those of ecological heterogeneity and provide some interesting insights into both the scale mismatch concept and the challenge of quantifying scale mismatches.

RESULTS

Scales of Data Layers on which Permits Were Based

Consideration of the areas of each polygon across all of the maps used in permitting showed that the maps have distinct median extents of their own (Figure 2). Analysis of the combined distribution of the areas of all polygons from these layers identified two dominant scales in the data at logarithmic means (±SD) of 1.14 ± 0.86 Ha and 5.8 ± 2.86 Ha (Figure 3). The densities of polygons under the curves were 21% and 79%. The dominant scales of polygons in the underlying coverages were thus 0.03 and 3.3 km^2; these are the values that would be expected under the null hypothesis that permissions were assigned randomly to mapped areas.

Scales of All Permission Data

The areas of all permissions for the GBRMP did not fall within a single normal distribution (Shapiro-Wilk W = 0.93, $p < 0.0001$). Gaussian mixture models with two, three, and four modes had log likelihoods of −27,137, −27,071, and −27,044, respectively. The best-fitting model (Figure 4) had two scales with logarithmic

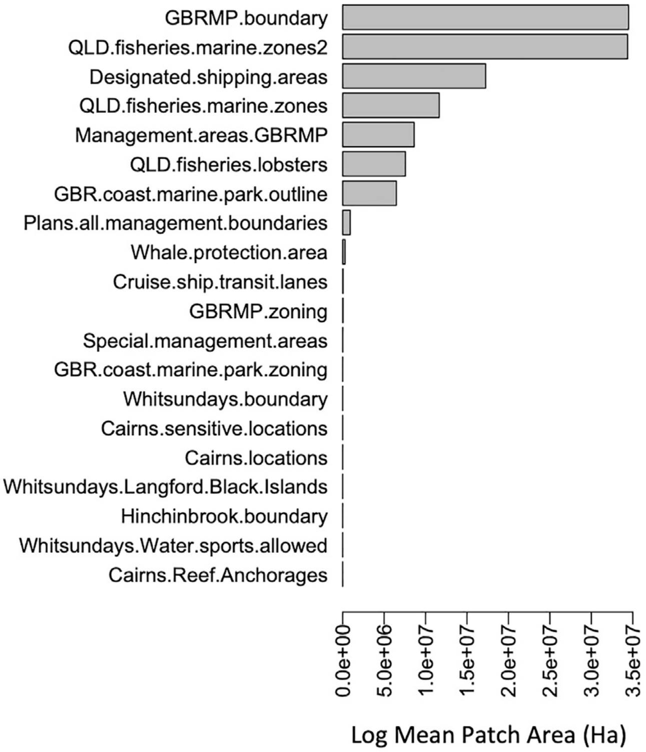

Figure 2. Mean Log Polygon Areas (km^2) for the 20 Different Shapefiles Used in the Analysis to Describe the Extents of Different Permissions

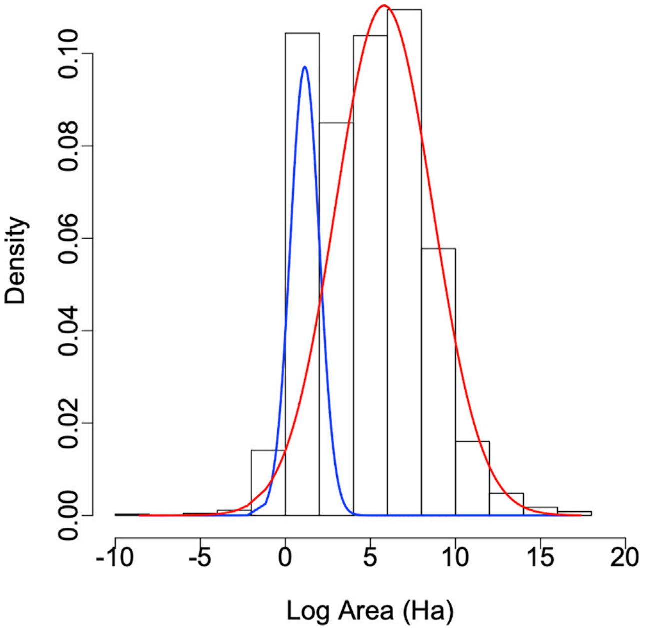

Figure 3. Density Histogram of Normal Curves Fitted with Gaussian Mixture Models to Polygon Areas in All Areas Used to Define Permits
Data are bimodal with distinct lower (blue) and upper (red) scales.

means (±SD) of 7.4 ± 3.18 and 16.1 ± 0.71. A likelihood ratio test of the two-scale model against a single-scale model indicated that the probability of finding data that far from unimodal if they came from a single true normal distribution was less than 0.0001. Both scales, and particularly the larger scale, are distinct from the counterfactual (i.e., areas of all polygons in the dataset) presented above.

Taking the exponents of our logged estimates and converting from hectares to square kilometers, these values corresponded to median values (equivalent to the geometric mean) of 16.4 and 99,542 km^2. Given that the GBRMP has an extent of 348,000 km^2, there thus appear to be two dominant scales of permissions within the GBRMP: a local scale (~4 × 4 km) and the other (~100 × 100 km) at roughly one-third (28.6%) of the extent of the GBRMP.

Scales by Permit Type

We determined the number and magnitude of scales for all permits and then for each different permit type (Table 1). Consideration of these data as actual values, rather than logarithms, suggests that there are three distinct scales at which permissions are issued (Figure 5). Interestingly, the upper scales of "access and transport" and "research and education" permissions formed the majority of permissions issued at broad scales (>80,000 km^2); the upper scales of permissions for tourism and events, pest removal, and resource extraction fell into a middle range between 363 km^2 and 6,700 km^2; and the scales of all other permissions, including the lower scales for the kinds of permission already mentioned and the upper and lower scales for all other permission types, fell below 41 km^2. Over the time period of the study, 72% of all permissions were fine scale and 28% were broad scale (Table 1).

Ecological Scales

The GBRMP features dataset describes the extents of reefs, cays, rocks, and islands. The Shapiro-Wilk test on the logged data indicated that the logged polygon area distribution was non-normal. Inspection of the histogram suggested that this deviation was due to skew rather than multimodality, resulting from a long tail of smaller features. Attempts to fit Gaussian mixtures to the features dataset were ambiguous (Table 2). A quantile-quantile (Q-Q) plot supported the view that the distribution was unimodal but deviated from the normal distribution at its edges. Skewness was −0.35 and kurtosis 3.4, suggesting a symmetrical distribution with heavy tails. We therefore treated this distribution as unimodal, with its median extent identified (with the use of mle*2* as described in the Experimental Procedures) at 3.73 (i.e., 0.41 km^2) and a logarithmic standard deviation of ±2.58.

The marine bioregions dataset describes non-reef habitats and excludes all reef, island, cay, and rock areas, so these areas were not analyzed twice. The distribution of polygon areas in this dataset was not significantly different from normal (Shapiro-Wilk test $p < 0.3$) and gave a single median value of 3.87 (0.48 km^2) with a logarithmic standard deviation of ±1.05.

Comparing Ecological and Institutional Scales

Comparing ecological and institutional scales (Figure 6), and keeping in mind that this figure has a logarithmic y axis, the ecological features that we considered occurred at finer scales

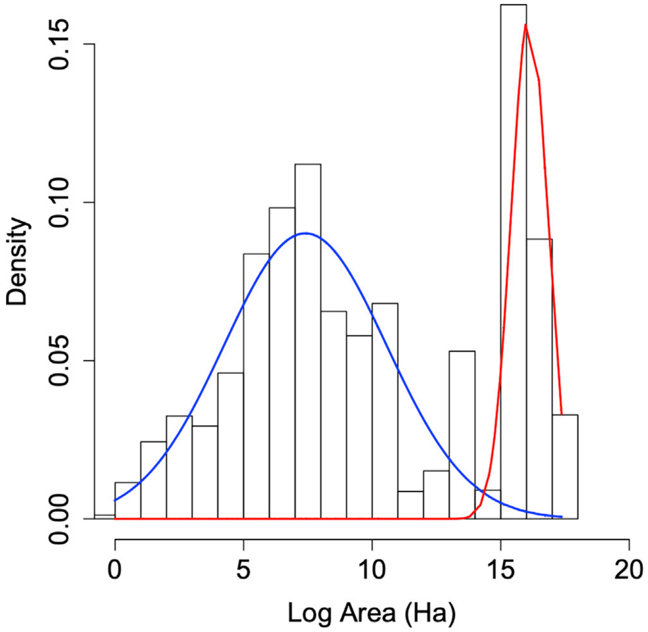

Figure 4. Density Histogram Showing Normal Curves Fitted with Gaussian Mixture Models to the Polygon Areas of All Permission Data

These data are bimodal with a distinct lower scale (blue line) and upper scale (red line).

than permissions. The values of the lower median extents of biophysical features were smaller than those of permissions. The lower values for most other permits ranged from 3.2 to 15 km^2, which is roughly 6–30 times larger than the measured scales of biophysical variation. The lower median values of permissions for pest removal (29 km^2) and research and education (36 km^2) and the upper median values of permissions for infrastructure (40 km^2), resource extraction (363 km^2), pest removal (1,193 km^2), tourism and events (6,600 km^2), research and education (88,861 km^2), and access and transport (99,194 km^2) were all at considerably broader scales. These subjective impressions were confirmed by statistical tests. Levene's test indicated that variances within groups were homogeneous ($F = 1.9$, $p < 0.19$), and the ANOVA confirmed that ecological modes were different from institutional modes ($F = 5.14$, $p < 0.04$).

DISCUSSION

Our analysis reveals the complex, multi-scale nature of some of the institutions that have been developed as management tools to regulate social-ecological interactions in the GBRMP. Permission data for the GBRMP were bimodal, such that permits were implemented dominantly at a single fine scale and a single broad scale with several orders of magnitude difference. The median extents of applicability of many permissions were much broader than the biophysical scales of reefs, islands, cays, and marine bioregions within the marine park. The median extents of permissions differed by permit type, such that infrastructure permissions were issued at the finest scales and "research and education" and "access and transport" permits were issued at the broadest scales.

The data provide clear evidence of discrete spatial scales of permissions across several orders of magnitude, and since these scales varied with permission type, they appeared to be sensitive to the nature and needs of different human activities. However, the premise that the scales of institutions (permissions) should correspond to ecological scales was not supported by the datasets that we considered. Our results thus support the first premise outlined in the Introduction but not the second. Obviously, in this exploratory analysis, we deliberately did not seek to be all-inclusive in our approach to quantifying the scales of ecological variation. The data that we have presented do not describe a series of much broader-scale ecological features and processes, for example, global biogeographic regions, oceanic currents and gyres, and the movements of far-ranging marine animals such as turtles and whales. Movement data for far-ranging marine organisms found in the GBRMP would quite likely reveal at least two different scales of movement, one encompassing local movements within the GBRMP and the other encompassing regional movements between the GBRMP and other marine habitats.[15–17] There is also a vast amount of finer-scale ecological variation within the GBRMP, for example, in the composition of reefs by depth and wave action and the spatial and temporal dynamics of stands of seagrass, mangroves, and mud flats.[18] Similarly, permit data offer just one first window into the scales of governance and management actions. Many other relevant activities, such as national legislation, compliance patrols, and fine-scale habitat management (e.g., protection of turtle nesting beaches, reef restoration, temporary closure of specific moorings or beaches), occur at additional scales that are not included in our analysis.

Keeping the various caveats on our analysis in mind, the precise details are less interesting than the insights that this first attempt to quantify and compare social and ecological scales offers into the demands of rigorous quantification of social-ecological scale mismatches. Two particularly important general findings emerge. First, permissions were issued across a wide range of areas, and their extents showed considerable variance within scales. Although discrete scales exist within the data, in all cases we were able to successfully fit Gaussian curves to log-transformed data, and many of the resulting distributions were smooth rather than discrete. The institutional data (permissions) thus comprise a series of overlapping, lognormally distributed areas rather than being either rigidly discrete or fitting a single statistical distribution. There is no single "scale of management." In addition, the nature of the statistical distributions for different kinds of activity differed. Context sensitivity has been highlighted by others as an important element of successful management frameworks,[19] and its occurrence in these data suggests a level of emergent adaptation in the permitting process. Our approach is thus capable of testing for scale sensitivity in management actions, which may be a useful indicator of social-ecological resilience.[20]

Second, permissions were often issued at broader extents than the ecological and biophysical features and the precise activities to which they referred. For example, a researcher who wants to collect samples from a particular species of sponge for a phylogenetic analysis may ask for permission to sample three or four different reefs but in practice will stop searching once they have found the specimens they

Table 1. Details of Statistical Tests to Establish Normality, Best-Fitting Models, and the Number of Modes for all Permissions and for Each of the Six Major Permission Types

Permit Type and Sample Size	Shapiro-Wilk W	Number of Scales in Best Solution	Gaussian Models: Mean and Sigma (Deviation) for Best Solution	Density by Mode (Lambda)	Gaussian Log Likelihoods for Candidate Models (Number of Scales)	BIC Values for Candidate Models
All permissions, n = 10,030	0.93, $p < 2.2^{-16}$	2	7.41 ± 3.18, 16.11 ± 0.71	0.72, 0.28	−27,136.93 (2)	−54,319.93
					−27,120.97 (3)	−54,288.01
					−27,043.98 (4)	−54,134.02
					−27,403.34 (5)	−54,132.75
Resource extraction, n = 2022	0.93, $p < 2.2^{-16}$	2	7.32 ± 1.97, 10.50 ± 4.32	0.73, 0.27	−4,994.84 (2)	−9,924.22
					−4,924.30 (3)	−9,886.68
					−4,868.74 (4)	−9,751.84
					−4,864.12 (5)	−9,329.53
Research and education, n = 379	0.925, $p < 7.6^{-13}$	2	8.18 ± 2.23, 16 ± 0.65	0.83, 0.17	−930.03 (2)	−1,889.74
					−928.27 (3)	−1,886.23
					−887.13 (4)	−1,803.95
					−914.38 (5)	−1,792.16
Tourism and special events, n = 894	0.92, $p < 2.2^{-16}$	2	6.35 ± 2.53, 13.4 ± 1.23	0.49, 0.51	−2,339.69 (2)	−4,713.35
					−2,264.29 (3)	−4,562.56
					−2,057.62 (4)	−4,149.22
					−2,025.81 (5)	−4,085.59
Access and transport, n = 4,346	0.81, $p < 2.2^{-16}$	2	6.72 ± 3.4, 16.11 ± 0.69	0.49, 0.51	−10,250.48 (2)	−20,542.84
					−10,170.73 (3)	−20,383.35
					−10,089.38 (4)	−20,220.65
					no convergence (5)	N/A
Infrastructure, n = 2,172	0.97, $p < 2.2^{-16}$	2	5.78 ± 2.92, 8.3 ± 2.57	0.59, 0.41	−5502.46 (2)	−11,043.33
					−5295.21 (3)	−10,628.84
					−5,382.02 (4)	−10,694.46
					−5,157.49 (5)	−10,353.40
Pest removal, n = 193	0.87, $p < 1.2^{-11}$	2	7.97 ± 1.48, 11.69 ± 4.73	0.64, 0.35	−479.11 (2)	−984.54
					−442.85 (3)	−912.01
					−422.45 (4)	−871.2
					−422.43 (5)	−871.19

Results are rounded to two decimal places. N/A, not applicable.

need; likewise, they will in practice remove only a few cubic centimeters of tissue despite formally having permission to sample across the entire reef. The practice of issuing permissions at broader scales than those demanded by the actual activity is supported by the managing agency as making life easier for the permitee and reducing administrative load; and preferred by the permitee as keeping their options open.[21] The obvious value of deliberately ensuring that management scales differ from ecological scales in this way suggests the hypothesis that creating rules at broader scales than the resource being managed is preferable to a direct correspondence of scales since it may allow a higher level of adaptation and responsiveness by human users. The deliberate creation of institutions that support flexibility by human users does, of course, also carry the alternative potential for abuse and overexploitation; hence, the same social and ecological fit could be beneficial in one situation and constitute a scale mismatch in another.

By most accounts, the GBRMP is well managed and effective, offering a good example of how a large marine protected area can be effectively administered.[22–24] Rather than interpreting our results as showing a scale mismatch, perhaps social systems *should* be managed at different scales to ecological systems in order to allow humans to more effectively integrate over the spatial and temporal variation that is inherent in ecosystems. There are presumably optimal scales at which the permitting process is both efficient and effective for each ecological scale and for permitees, and it is possible that over time, the permission data have started to converge on these scales; unfortunately, we do not have the necessary additional data on actual scales of use by permit holders to test this hypothesis.

Explicit analyses of scale mismatches should in theory offer a useful diagnostic tool for identifying activities and management needs where social and ecological processes and patterns are poorly aligned. Translating scaling analyses into management recommendations is, however, harder than it might appear.

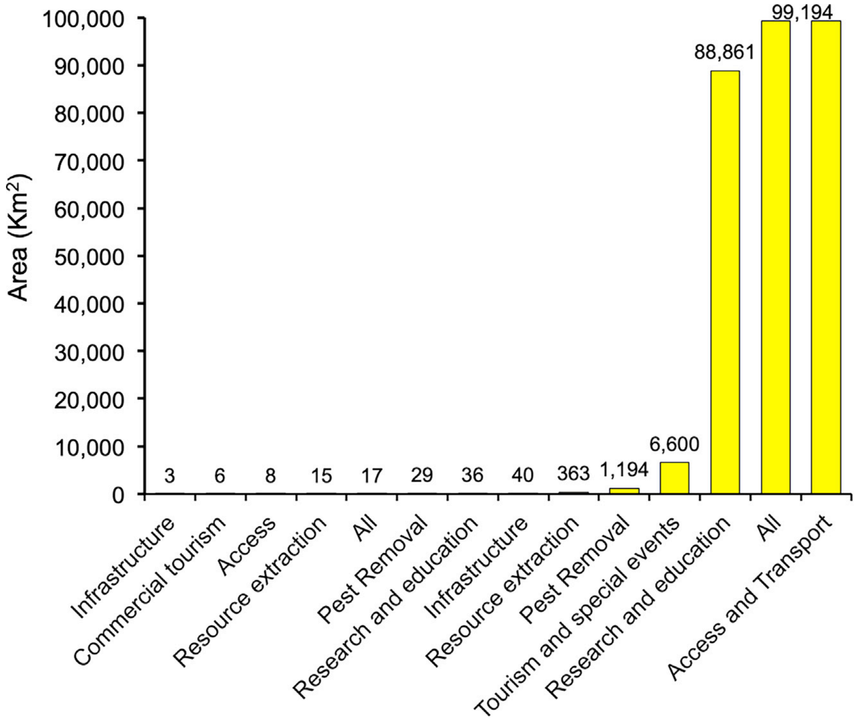

Figure 5. Bar Chart Showing the Median Values (Geometric Means) of All Scales for All Permissions by Permission Type (km^2)

Data are summarized in Table 1.

Would we be able to conclude from our analysis that there is no social-ecological scale mismatch within the GBRMP? One of the challenges in answering this question is that we currently have no other frame of reference for how real-world scales of social and ecological pattern align. Building such a frame will require empirical data from a range of diverse case studies, including cases where management is known to be dysfunctional or ineffective; and ideally incorporating quantitative measures of management effectiveness and actual use.

In any map, there is usually only one boundary polygon and many smaller features that are contained within the boundary; hence, there will almost always be fewer polygons at broad scales than at fine scales. If permissions were randomly assigned to polygons, then there would be very few extensive (broadest-scale) permits, so strongly log-normal distributions of permissions would be expected in the null or neutral case if permits were randomly assigned to polygons. Studies of scale mismatches that seek to rigorously quantify scales and interpret the resulting patterns will need to develop and use appropriate null models and explicit counterfactuals to determine whether and how the empirical data differ from an expected null or neutral model. An additional consideration for our particular case study is that the primary known threats to the GBR come from outside its borders, specifically in the form of climate change (a global phenomenon) and water quality declines due to terrestrial runoff (a regional concern).[25–27] The Great Barrier Reef Marine Park Authority (GBRMPA) has no direct power to solve these problems, although it can act as a stakeholder and collaborator in working for improved governance and management of external systems.

The question also arises of whether we have lost key information by analyzing scales in aggregate (i.e., comparing data at the level of two inter-related populations) rather than considering each social-ecological pair individually. As discussed in more detail in the Supplemental Information, this is not the case because if the scales of individual pairs of permissions and the ecological features to which they refer were strongly aligned, and if they clustered at distinct scales, then pairing would leave a strong signature on the frequencies of the different polygon areas. There are many good examples of aggregate or population-level approaches being applied successfully to understand questions of body mass, scaling, and habitat use;[28] while our approach is novel in this particular context, similar methods have been widely used in ecology.

This exploratory analysis has demonstrated that institutional and ecological scales can be directly measured and compared. It represents a first step toward a more rigorous empirical grounding of the science of social-ecological scale mismatches. With a wider range of datasets and comparative analysis between different case studies, ideas about scale mismatches have the potential to become a useful practical and diagnostic tool for management and for quantifying cross-scale influences rather than just a conceptual tool. At the same time, confronting the scale mismatch concept with data shows how simple conceptualizations of "scales of management" and "scales of ecological variation" can be misleading; management occurs across a wide range of scales, and management of people and their activities may in fact be more effective if undertaken at different scales from those of ecological variation.

EXPERIMENTAL PROCEDURES

Resource Availability

Lead Contact

Further information and requests for resources should be directed to and will be fulfilled by the Lead Contact, Graeme Cumming (gscumming@gmail.com). The permit data were made available by the GBRMPA.

Materials Availability

This study did not generate new unique materials.

Data and Code Availability

There are restrictions to the availability of these data because of the associated personal details and confidential nature of the permits. Code for the R analyses used standard statistical libraries that are available from the R-CRAN web site.

Permit Data

Permits are a form of institution, specifically rules-in use.[21,29] Our focus for this analysis was on understanding the scales of institutions (as defined in permits) issued by the GBRMPA rather than on the ways in which institutions translate into direct use of (or impacts on) the GBRMP. Unless otherwise specified, we use "scales" throughout this paper to refer to the different orders of magnitude covered by the mean or median area(s) associated with permissions or ecological features. Many management activities that occur within the GBRMP are

Table 2. Summary of Results for Analyses of the Scales of Ecological Features in the GBRMP

Ecological Dataset and Sample Size	Shapiro-Wilk W	Number of Modes in Best Solution	Gaussian Models: Mean and Sigma (Deviation) for Best Solution	Density by Mode (Lambda)	Gaussian Log Likelihoods for Candidate Models (Mode Numbers)	BIC Values for Candidate Models
GBRMP features (reefs, islands, rocks, cays), n = 5,359	0.991, $p < 2.2^{-16}$	1	3.73 ± 2.57	1	−12,683.46 (1)	−25,384.10
					−12,657.39 (2)	−25,357.72
					−12,608.01 (3)	−25,268.29
					−12,601.39 (4)	−25,258.95
					−12,607.37 (5)	−25,245.71
GBRMP marine bioregions (excluding reefs and islands) merged by habitat type, n = 42	0.969, $p < 0.30$	1	3.87 ± 1.05	1	−61.64 (1)	−130.76

Further details in text.

not captured in the permits database, so our dataset is not exhaustive. Permits do, nonetheless, offer a rich and spatially explicit window into the social-ecological fit of management activities.[21,30]

We analyzed data on 10,030 permissions, contained within 7,478 permits issued between 2007 and 2017, to quantify the spatial institutional scales at which the GBRMPA grants permission to undertake different kinds of activity within the park. The permit data were provided by GBRMPA. The dataset has been described in more detail by Cumming and Dobbs.[21]

Each individual permit record contained information about the operation and location for which permissions to undertake a given activity were requested. One permit might contain several different permissions. For example, a tourism-related permit might include permissions for the conduct of a tourism program, the installation, operation, and maintenance of a facility such as a pontoon, and the conduct of a vessel or aircraft charter operation. We treated each of these permissions separately due to differences in their scale and focus. Each individual permission must be requested individually, so co-occurring "bundles" of different permission types describe genuine trends within the data rather than spurious correlations. Users must explicitly request and justify permit durations. Tourism permits are generally issued for up to 6 years, with exceptions for eco-certified operators who can obtain permits for up to 15 years. Research permits usually run for around 3 years (i.e., the length of a typical PhD project or research grant). We initially aggregated activities into 46 different classes of permission, as detailed by Cumming and Dobbs,[21] later merging these into six broader classes. The six classes included (1) commercial resource extraction (e.g., harvest fishing for lobster and sea cucumber, coral collection, and aquarium trade), (2) research or education (e.g., scientific research and educational tours), (3) non-extractive tourism and special events (e.g., commercial snorkeling and diving tourism, water sports, fireworks shows, and beach hire), (4) access and transport (e.g., cargo barges, boat hire, and airplane landing), (5) built infrastructure (e.g., moorings, marker buoys, power cables, pontoons, and other facilities), and (6) pest removal (e.g., *Acanthaster* sp. crown of thorns starfish and *Drupella* sp. snails).

To quantify the spatial scale(s) at which permits were issued, we used R to link the permit data to each of the 20 different shapefiles identified by Cumming and Dobbs[21] and in Figure 1 and extract the area covered by each permission within a permit. A single permit may cover several different, possibly even disconnected locations and several different activities ("permissions"). Since we wished to explore the differences in spatial scale between different kinds of permission (institution), our level of analysis was permissions rather than permits. This meant that some individual permits contributed more than one polygon to the analysis and that the same polygons might be counted several times under the same permit if different individual permissions were given in the same permit. For example, a commercial tourism operation might require individual permissions for each of its three vessels to access the same offshore location (three identical polygons, all for access), to use a beach (one polygon of type "tourism and special events"), and to undertake a specific activity, such as a guided tour (one polygon of type "tourism and special events"). These activities might all use the same location name, in which case the same value for polygon area would appear eight times in the dataset; or there might be different locations specified for different activities (e.g., access via water, activity near an island), in which case each different location would be described by a different polygon. The number of permissions granted per polygon across all permits varied from 1 to 609, with a median of 2 and a mean of 10.91.

Spatial Data

We obtained spatial data layers (shapefiles) for all locations mentioned in the permit data, reprojected all data into an Australian Equal-Areas Albers projection, and manually captured the shapefile identity and the identifier of the polygon for each individual permission. A total of 321 permissions from the original 10,351 permissions could not be located reliably and were excluded from the analysis, leaving a sample size of 10,030 permissions. We required 20 different shapefiles from three different agencies (GBRMPA, Queensland Parks, and Queensland Fisheries) to represent all of the data (Figure 1). These shapefiles included three localized and more intensive management plans within the GBRMP for areas near the Whitsundays, Cairns, and Hinchinbrook. Although some maps (e.g., the zonation plan for the GBRMP) are heavily used in defining permit locations, we did not analyze all polygon scales individually for each shapefile because we have presented an analysis across all shapefiles as a null hypothesis; in addition, the areas defined in these maps are already implicit in the permission data, and many polygons were not used in issuing permissions.

To measure the mean areas of relevant ecological features, we used different, publicly available coverages[31] for (1) GBRMP features (shapefile Great_Barrier_Reef_Features.shp; polygons describing all reefs, atolls, islands, cays, and rocks) and (2) non-reef marine bioregions (shapefile Marine_Bioregions_of_the_Great_Barrier_Reef__Non_Reef, which describes non-reef marine habitats).[32] It is important to note that the marine bioregions are not defined from *a priori* management units; rather, they describe ecosystem-level heterogeneity between locations on the basis of differences in substrates and ecological communities, in much the same way as terrestrial ecoregions. In the publicly available database, the non-reef marine bioregions have in many cases been artificially subdivided into smaller units. We merged these units by habitat type prior to analysis, reducing the dataset to 42 different polygons (as displayed in Figure 1), to ensure that we captured ecological rather than management-related features. The reef bioregions data were not included separately because they have the same scales as the GBRMP features data. Coverages were first reprojected into an Australian Equal-Areas Albers projection. We then extracted the extents of all polygons and applied the same methods described for the permit data to quantify ecological scales. We did not include measures of connectivity, ocean currents, perturbations, or propagule transport[33,34] in our assessment of scale because these more dynamic ecosystem attributes are treated as external influences in GBRMPA's permitting system

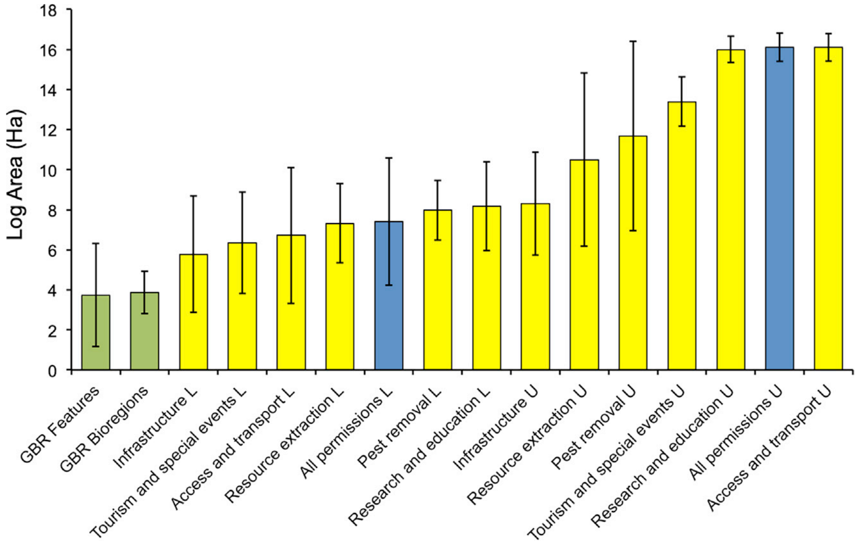

Figure 6. Bar Chart Showing Log Areas (Ha) of Relevant Scales

Included scales are all permissions (blue), the six main types of permission (yellow), and ecological features and bioregions (green) in the GBRMP. Error bars indicate one standard deviation of logarithms above and below the mean. All permission datasets had two distinct scales; labels distinguish between the upper scale, U, and lower scale, L.

Statistical Analysis

The relationships between different datasets are influenced by landscape structure in the sense that permits are issued for some particular areas that are defined by biophysical elements (e.g., reefs or islands) and for some locations that are arbitrarily defined by people but have some relationship to the biophysical environment (e.g., the GBRMP boundary encircles the majority of shallow-water coral reefs off the east coast of Australia). Entrainment of the spatial scale of human management actions by ecosystem heterogeneity was the focus of our analysis; the relationship between scales of permits and scales of ecosystem features was thus the variable of interest rather than a nuisance variable that needed to be factored out. However, we also wanted to check whether our analysis was constrained by the underlying statistical distribution of mapped features. As a reference point, we therefore started by measuring the areas of all polygons in each of the 20 spatial data layers that were used in defining the boundaries of permits. We then measured the areas of all polygons for all permits, for each type of permit, and for selected ecological features.

To quantify the scales at which social-ecological matches and mismatches might be expected to occur, we used the distributions of polygon areas. Since the dataset was strongly dominated by smaller polygons and the most appropriate techniques for quantifying scale are parametric, we used the logs of areas for all scaling analyses. We quantified the mean extents of management by fitting normal curves to logged area frequency data and using the mean, deviation, and proportional area of each curve to describe scale. Since these curves were symmetrical, the mean and the mode are identical, and their values describe the dominant scales in each dataset. Further explanation of our estimation and interpretation of the extents of social and ecological features are given in the Supplemental Experimental Procedures.

Both the ecological and the institutional (permit) data were initially visualized as histograms and explored with the use of descriptive statistics. We have reported median values rather than mean values when comparing institutional and ecological data since converting log-transformed means back to original values produces a geometric mean and not an arithmetic mean; the arithmetic mean will be greater than or equal to the geometric mean. Similarly, reported standard deviations are deviations in logarithmic values and cannot be accurately converted back to areas.

We tested each logged dataset for normality with a Shapiro-Wilk test (*shapiro.test*), according to Razali and Wah,[35] by using a random selection of 5,000 data points where n > 5,000. In the one instance where the logged data were normally distributed (non-reef marine bioregions), we simply estimated areal scale as the mean of all logged polygon areas. We determined the number of areal scales and their magnitudes using Gaussian mixture models. Gaussian mixture models are widely used to separate overlapping normal distributions into their respective populations. They have found previous application in ecology for such problems as distinguishing scale dependency in predator foraging behaviors,[36] classifying vegetation types[37] and animal mating calls,[38] and determining co-occurrences of individuals in movement networks.[39]

We fitted Gaussian mixture models to logged data using the *normalmixEM* function in the *mixtools* package in R.[40] We fitted models iteratively at values from 2 to 10 scales by using a convergence criterion (epsilon) of 0.001. We used the absolute value of the negative log likelihood and the Bayesian Information Criterion (BIC) for each model to guide model selection (i.e., selecting the model with the highest absolute log likelihood and favoring the most parsimonious model if BIC values were similar) and checked each fitted model visually to ensure that model fit looked reasonable. Since *mixtools* does not always converge consistently to a solution, we ran the model fitting procedure five times on the best-fitting model to check that it was stable, again by taking the model with the highest absolute log likelihood and BIC if there were any variation in model fit. The *mixtools* package does not cope well with unimodal data, so where distributions could potentially be or have been unimodal, we used the mle2 function in the *bblme* library to estimate log likelihoods and BIC values as well as look at Q-Q plots and additional statistics (kurtosis, skewness, and Silverman's test) to determine the number of scales. After determining the number of scales occurring in each dataset and their magnitudes, we tested for differences between the magnitudes of different scales from ecosystems and permissions, first by using Levene's test in the *car* package in R[41] to determine whether variances were homogeneous between groups (institutional versus ecological) and then a one-directional ANOVA.

SUPPLEMENTAL INFORMATION

Supplemental Information can be found online at https://doi.org/10.1016/j.oneear.2020.07.007.

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AUTHOR CONTRIBUTIONS

G.S.C. conceived the manuscript, analyzed the data, and wrote the first draft of the manuscript. K.A.D. facilitated data access, helped interpret data, and co-wrote the manuscript.

DECLARATION OF INTERESTS

G.S.C. has no competing interests. K.A.D. is an employee of GBRMPA, the management agency whose permit data and management approach are discussed in this manuscript.

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