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Research Article

Using Google Earth to improve the management of threatened limestone karst ecosystems in Peninsular Malaysia

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Abstract

In a world of limited resources and so many species and habitats in need of protection, informed prioritization is essential. However, we cannot prioritize effectively if historical and current information regarding a particular habitat or species remains scattered. Several good platforms have been created to help users find, use and create biodiversity information. However, good platforms for sharing habitat information for threatened ecosystems are still lacking. Limestone hills are an example of threatened ecosystems that harbor unique biodiversity, but are facing intensifying anthropogenic disturbances. As limestone is a vital resource for the construction industry, it is not possible to completely halt forest degradation and quarrying in developing countries such as Malaysia, where 445 limestone hills have been recorded in the peninsula to date. As such, there is an urgent need to identify which hills must be prioritized for conservation. To make decisions based on sound science, collating spatial and biological information on limestone hills into a publicly accessible database is critical. Here, we compile Malaysia's first limestone hill GIS map for 445 limestone hills in the peninsula, based on information from geological reports and scientific literature. To assist in conservation prioritization efforts, we quantified characteristics of limestone hills in terms of size, degree of isolation, and spatial distribution patterns. We also assessed the degree of habitat disturbance in each limestone hill in terms of buffer area forest degradation and quarrying activity. These data are stored in a KMZ file and can be accessed through the Google Earth interface. Rather than being viewed as a final output containing basic limestone hill information, this database should be regarded as a foundational platform for users to collect, store, update and manipulate spatial and biological data from limestone hills to better inform decisions regarding their management.

Keywords: spatial analysis, forest degradation, species extinction, Keyhole Markup Language, caves, QGIS, SAGA GIS, mykarst

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Introduction

In a resource-limited world that is rich in biodiversity, we have to make difficult choices about which habitats of an ecosystem or which populations of a species to conserve [1-2]. However, conservation priorities cannot be identified unless ecosystems are quantified and mapped [3-4]. With advancements in remote sensing technology, different ecosystems, such as forests, rivers and lakes, can now be detected and be mapped effectively. Ecosystems that have yet to be adequately mapped include limestone hills, which cover about 11% of the Earth's surface [5].

Limestone hills in the tropics are regarded as "arks" of biodiversity as they contain high levels of species endemism [6-9]. Quarrying of limestone hills represents the most direct threat to their biodiversity as it causes irreversible destruction of habitats [7, 10]. In addition, degradation of forests on and around limestone hills can result in negative impacts on their biodiversity, too [11]. In fact, many species that are endemic to limestone hills are already extinct or on the brink of extinction [9,12]. There is thus an urgent need to prioritize limestone hills for conservation as they continue to be exploited, particularly by the cement industry [7, 13].

In Malaysia, karstic areas with limestone hills are vital components of the country's geoheritage [14]. Many of these hills were once connected and belong to the same geological formation or bedrock. Some, however, are lenticular and were never connected to other hills [15]. The hills distribute unevenly across Peninsular Malaysia, and almost all of them (> 95%) are found in the four states of Kelantan, Pahang, Perak, and Perlis. However, information regarding the location of limestone hills in the country remains scattered in the literature.

The most reliable information sources have been geological reports that include maps illustrating the location of limestone hills in a given area (see Supplementary Information 1). Several rather comprehensive gazetteers are also available but, in most cases, they provide only names, approximate coordinates, and descriptions of the limestone hills without complete maps of where they are located [16-17]. To date, there are no publicly accessible, free, complete, reusable, easily editable and scientifically rigorous maps of limestone hills available for scientific research and management.

Remote sensing technologies have had moderate successes in detecting limestone hills in tropical regions where they are subject to more intensive and continuous weathering [18-20]. The efficiency of the detection from remote sensing approaches depends on the scale, sensor and the geomorphology of the limestone [21-22]. However, many of the limestone hills in tropical regions such as Malaysia are very small, often without visible geomorphological features, and are covered by forest. To distinguish them from regular hilly forests using remote sensing alone poses a challenge.

A conservation prioritization exercise is needed to improve the management of this threatened ecosystem, particularly because it is not possible to protect every limestone hill in Malaysia due to economic demands. Before this can be done, baseline scientific data is needed for each limestone hill, documenting physical characteristics and the degree of threat they face from environmental impacts. After that, information can be added as it becomes available regarding their geological, archaeological and biodiversity importance. Unfortunately, at present such data is only available for a small number of hills and the different datasets have yet to be integrated into a single database. One of the main challenges to setting up such a database is a lack of resources (i.e. time and money) and expertise to gather these kinds of scientific data. Another fundamental problem is that there is no general reference scheme to identify limestone hills; different studies often use different names for the same hill, and this is problematic for data integration.

In view of these issues, we have developed a working limestone hills GIS map for Peninsular Malaysia. First, we compiled localities of known limestone hills in the region from a variety of publications and digitized them in a KML (Keyhole Markup Language) format file. With this database established, we then conducted a preliminary conservation prioritization exercise for limestone hills by quantifying their 1) physical parameters based on size, degree of isolation, and spatial distribution patterns; and 2) threat parameters based on the presence/absence of quarrying and the degree of habitat disturbance in terms of buffer area forest degradation. Finally, we saved these outputs as a KMZ file for public access via the Google Earth interface.

Methods

Limestone hills mapping

We manually compiled limestone hill data from a variety of sources and systematically transferred them into an accessible GIS database using a multi-level approach similar to GIS remote sensing approaches (e.g. [19]). First, we extracted localities of limestone hills from 61 publications, which were mainly geological references that included good quality geological maps. We did not include hills that were only identified by coordinates. We excluded the limestone hills on the offshore islands.

Second, we marked these hills in Google Earth as polygon placemarks and annotated them with their reference source in the "description" field of the placemark. Due to its rich temporal repository of high resolution images, most of the hills were visible on Google Earth. Recent forest loss and monoculture crop plantations around limestone hills have also made them more prominent and readily identifiable. However, several limestone hills were very small and covered by forest, which sometimes made them indistinguishable from the surrounding forest. As such, we used the shape of the hills from relevant maps to verify their location.

Third, we added additional hills, based on unpublished field notes, that were omitted from the literature. Lastly, digitization of the hills was performed directly in Google Earth by tracing the outline of the limestone outcrop as a polygon. At the same time, the code/name of the hill used by those references were tabulated in the description field of the polygon properties, for example: [Source: Gobbett, 1967]<Hill name: Bukit Biwah>. For hills that were already listed in the most comprehensive gazetteer for limestone hills in Peninsular Malaysia [17], we used the hill reference number and name for the name of the polygon. For hills not listed, or ones that could not be verified in Price [17], we used the prefix "mykarst" followed by unique numbering (i.e. 001 onwards). The digitized outline and reference information for each hill were saved in a single KML file to be analyzed and modified later.

Quantifying limestone hill physical parameters

Figure 1 illustrates the steps involved in this process. First, we converted the KML file consisting of 445 limestone polygons into a polygon limestone hill shapefile (*.shp), which has a Universal Transverse

Mercator coordinate system. Next, we quantified the limestone size, degree of isolation and distribution patterns from this shapefile by using QGIS version 2.8.3 – Wien [23]. Last, we plotted the hill size against the degree of isolation to explore their irreplaceability: larger and more isolated hills are considered more irreplaceable as they are more likely to have higher biodiversity and endemic species based on the central tenets of island biogeography. All the GIS data can be found in Supplemental Information 2 (see page 920 for supplemental information for this article).

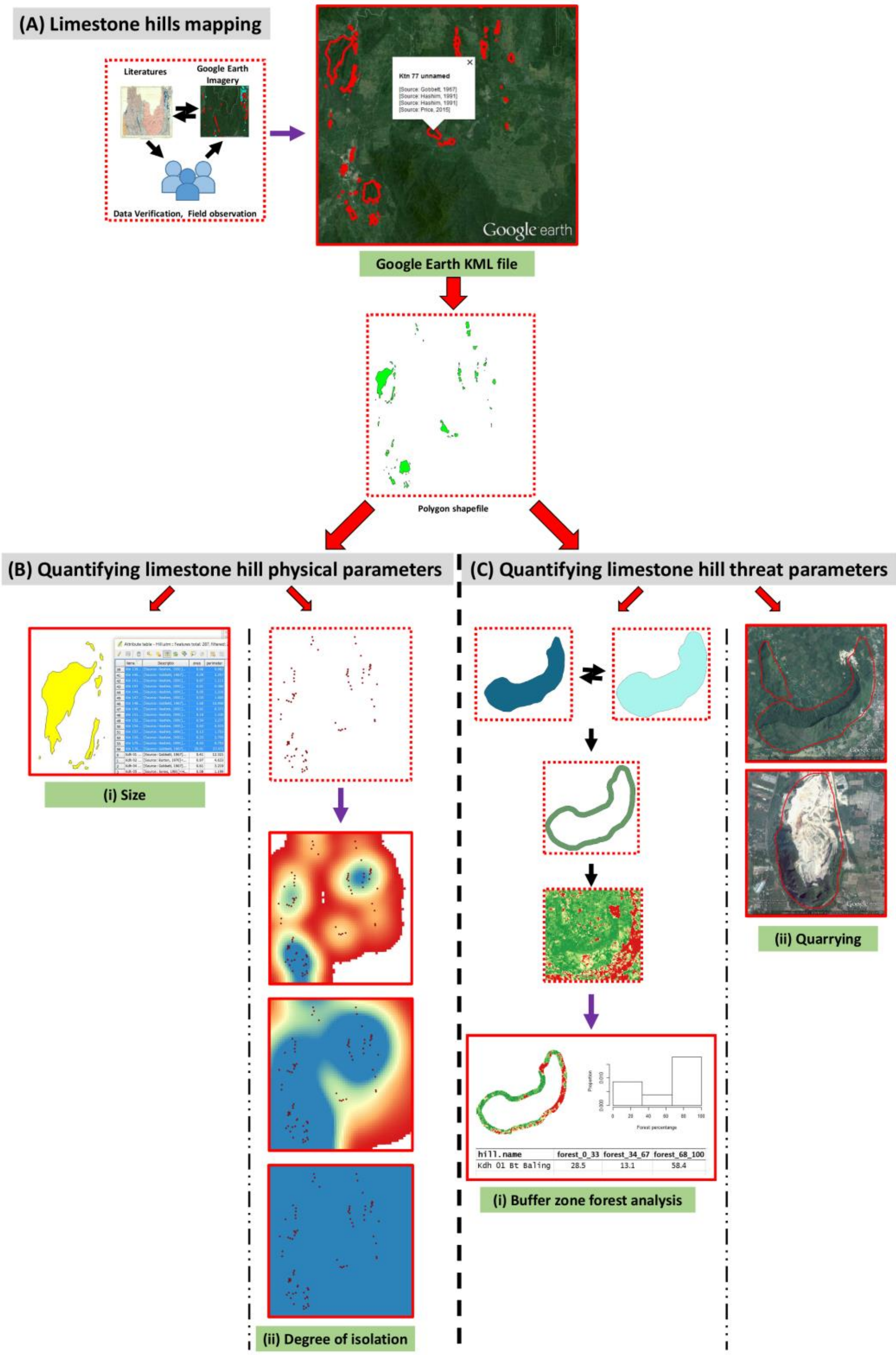

Fig. 1. Analytical flowchart for this study. (A) limestone hills mapping; (B) quantifying limestone hill physical parameters – (i) size and (ii) degree of isolation; (C) quantifying limestone hill threat parameters – (i) buffer zone forest status and (ii) quarrying.

To calculate the size of each limestone hill (i.e. area; km^2), we used the "Geometry$area" functions of the "Field calculator" in the attribute table of the shapefile. A series of histograms with different bin sizes were produced to examine the distribution of the limestone hill sizes in Peninsular Malaysia.

To calculate the degree of isolation of each limestone hill, we converted the hill polygon shapefile into a point shapefile so that each hill was represented by its centroid point, using the "polygon centroid" function. After that, we generated limestone density raster layer with a cell size of 50 meters by using "Heatmap analysis" for radiuses of 10km, 25 km and 50 km respectively. Next, we used "Add grid values to points", in SAGA version 2.1.4 [24], to extract the density values of the output layers of "Heatmap analysis" for each limestone hill (centroid) to the limestone hill point shapefile's attribute table.

The three density values were used as the degree of isolation of each limestone hill in three different spatial contexts. For example, a limestone hill with a raster value of 4 in the 10 km heatmap raster layer meant that there were three other hills within a 10 km radius. The small spatial context (e.g. 10 km search radius) was useful for visually identifying clusters of isolated hills in Peninsular Malaysia, whereas the larger spatial contexts produced a generalized density map where clusters could not be easily identified. In this way, an extremely isolated hill should have lower density values for all spatial contexts, while an isolated limestone cluster should have a higher value in the small spatial context but a lower value in larger spatial contexts. We then explored limestone hills' density values for all spatial contexts by using histograms to identify isolated single hill and limestone clusters, in which several separate hills were situated in close proximity to each other, but far from other limestone clusters. All the plots were made using R version 3.2.2 [25].

Quantifying limestone hill threat parameters

To determine the quarrying disturbance of limestone hills, each hill of the KML polygon file was inspected visually from Google Earth for the presence/absence of quarrying activity. Due to resource constraints, we were not able to conduct ground-truth verifications to determine whether the quarrying sign of a limestone hill indicated an abandoned or active quarry.

To assess the forest status at the buffer zone, we used the buffer zone polygon shapefile of each limestone hill and published forest status maps from the literature. For forest status maps, we used the Landsat datasets of Hansen et al. [26], which provided data on tree canopy cover in the year 2000. The layer had a grid size of 1 arc-second (~30 meters) and each grid cell had a percentage value in the range 0–100 for all vegetation taller than 5 m. In addition, we also used forest gain layer and forest loss layer, following Hansen et al. ([26]; accessed Dec 2015). The details of these layers are available at http://earthenginepartners.appspot.com/science-2013-global-forest/download_v1.2.html. We converted the coordinate system of these layers into UTM (Timbalai 1948 / UTM zone 50N - EPSG:29850 - EPSG.io). We were aware that there were other forest maps derived from different remote sensing imageries with different resolutions, such as [27-28]. However, large forest extent maps created using simple algorithms are not without weaknesses and discrepancies [29-30]. In fact, using a high resolution forest map of Peninsular Malaysia is critical for a buffer zone analysis involving relatively small features such as limestone hills. Until this kind of map is available, we felt it was necessary to conduct an exploratory analysis of the forest condition in the limestone buffer zone using the most suitable map for our purpose (i.e. [26]).

Next, we documented the 250 m buffer zone of each hill based on polygon limestone hills shapefile. After that, the area size of this buffer zone was calculated. All the three forest status layers were cropped by this buffer zone. For the forest cover layer, cell values ranging from 1-100 were summarized into three bins in histogram, namely, (1) 0-33; (2) 34-67; and (3) 68-100, for each hill. The forest gain layer and forest loss layer were recalculated to produce a new layer that represented both net forest loss and gain in the buffer zone of each hill. Lastly, we explored the forest status of each hill by plotting the proportion of 'good' forest (value 68-100) against the proportion of net forest loss in the buffer zone of each hill. All these analyses were done in R environment by using Packages "raster" [31], "rgdal" [32] and "rgeos" [33].

Creating a limestone GIS database in the form of a KMZ file

In order to create a publicly accessible and user-friendly limestone GIS database, we incorporated the digitized map, references, limestone physical and threat parameters into a single KMZ file that can be accessed via Google Earth interface. We used as a template the same KML that already had digitized limestone hill outlines and reference information. After that we summarized each limestone hill's physical and threat parameter into one overall graph that consists of six plots and maps (Fig. 2). Lastly, we updated the script of the KML template to include the graph by a short custom written R script (Supplementary File 2).

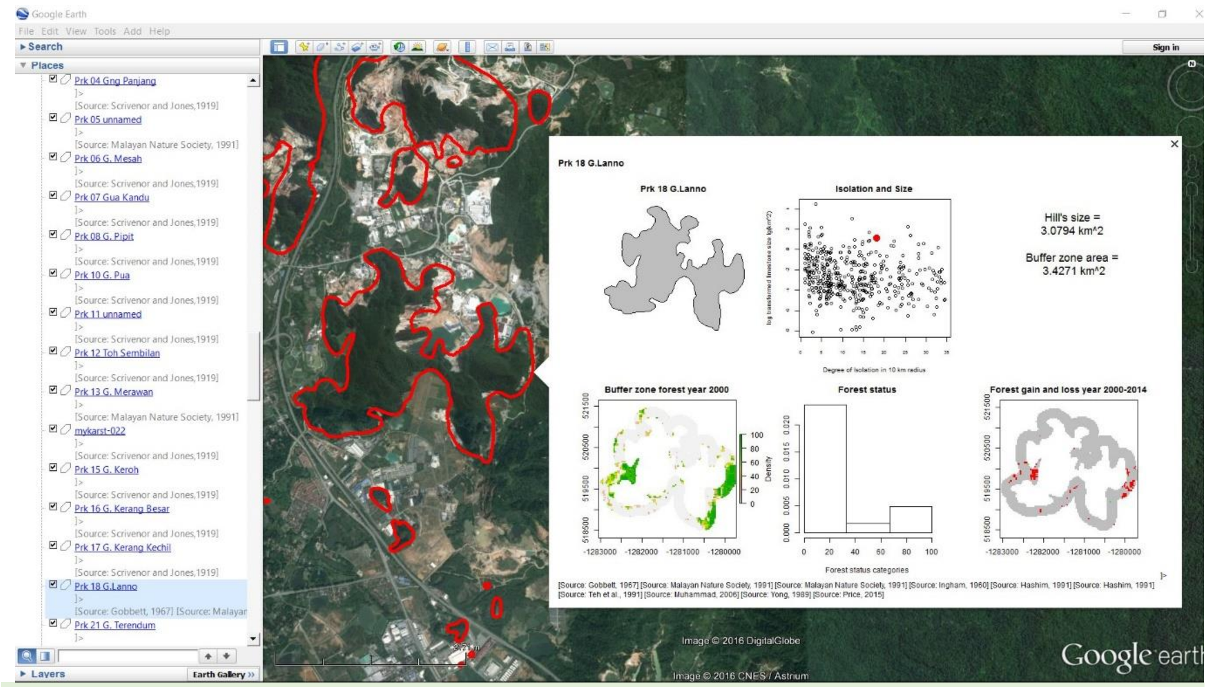

Fig. 2. A screenshot of Peninsular Malaysia limestone hills GIS database that was opened in Google Earth. The outline of each limestone hill is shown, and when selected ("click"), a pop out window shows the name, an overall graph and the references. The overall graph consists of: Top row (left to right) – a Fig. of limestone hills outline, a scatterplot shows the size and isolation of the hill in the context of other hills in Peninsular Malaysia, and hill and buffer zone area size; Bottom row (left to right) – map of forest status (i.e. Hansen et al., 2013) in buffer zone in year 2000, a histogram that summarized forest status in buffer zone in year2000, and a map shows the forest net gain and net loss in buffer zone between year 2000 – 2014.

Results

Limestone hill mapping and the GIS database

In total we digitized 445 hills via Google Earth based on the literature (Fig. 3). Of Peninsular Malaysia's total land surface of 130598 km^2, only 280 km^2 (~0.2%) is covered by limestone hills. The frequency of each limestone hill mentioned in the references is documented in Supplementary Information 1: Figure S1).

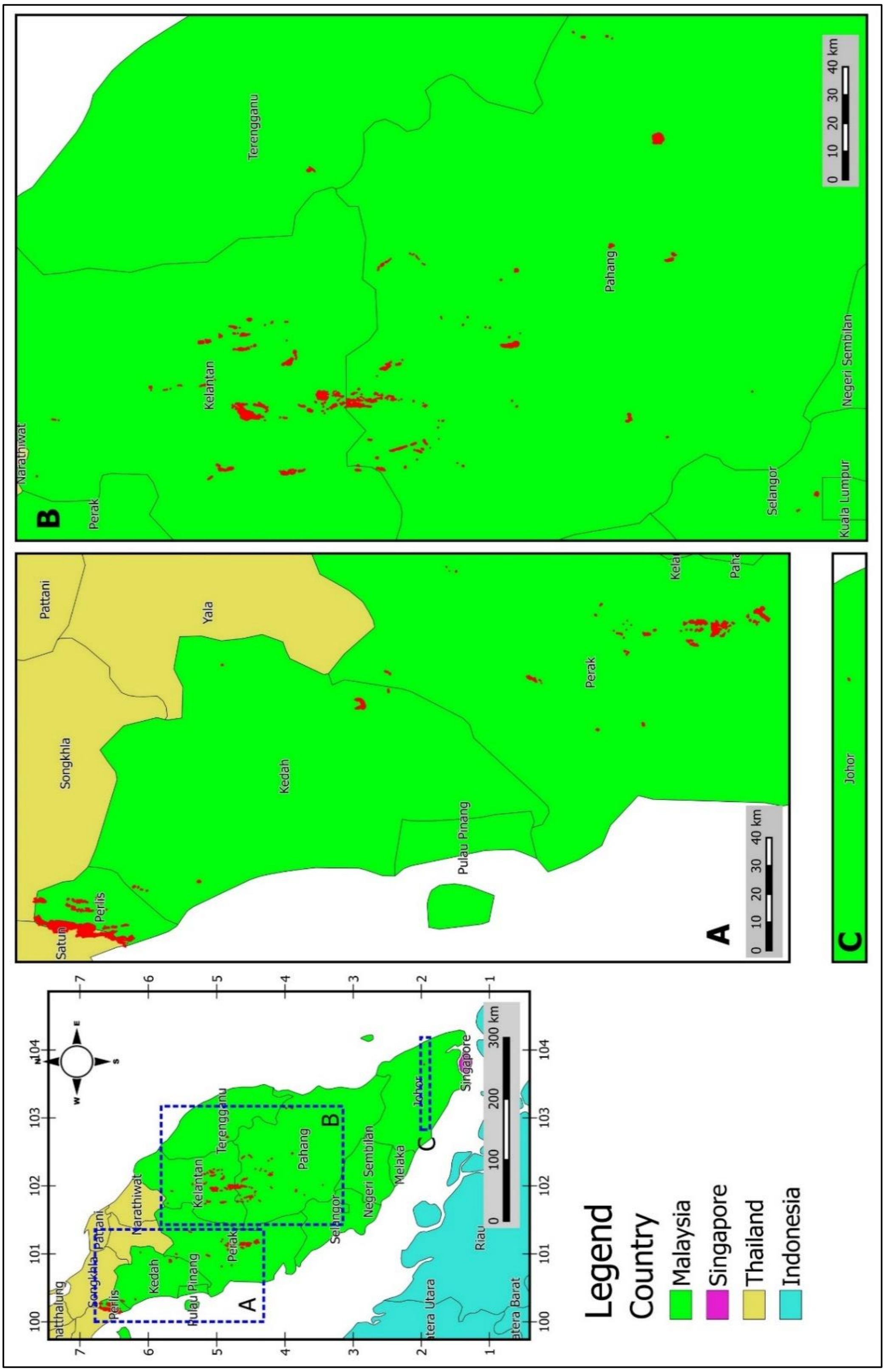

Fig. 3. Maps of limestone hills in Peninsular Malaysia.

During the collation of the spatial data, we found two interesting patterns. First, 81 of 445 limestone hills were mentioned only once in the references that we surveyed; for the majority of hills, the karstic area of a particular hill was mentioned by more than one reference. Second, many of the limestone hills that were recorded numerous times revealed inconsistencies among hill names, including well-studied limestone hills (such as “Prk 27 G. Datuk”, “Prk 29 Gunung Lang”). The original KML polygon file of these digitized hills can be found in Supplementary File 3.

The state of Kelantan has the most hills – 149 (33.5%), followed by Pahang – 124 hills (27.9%), Perak – 93 hills (20.9%), and Perlis – 60 hills (13.5%). The remaining 19 hills (4.25%) are at Kedah – 12, Selangor – 3, Terengganu – 3, and Johor – 1 (Fig. 3). We created a GIS database in a single KMZ with a small file size (34.6 MB). It contains basic information on the physical and threat parameters of each of the 445 hills that can be accessed via Google Earth. In addition, advanced users can create a newer version of this database (KMZ file) by adding or deleting hill outlines in the original KML file according to the needs of the user (for example, some users may want to conduct a conservation prioritization exercise for hills in a single state). Our analyses can be repeated for different user scenarios by following the analytical workflow described above and R script (Supplementary File 2).

Limestone hill physical parameters

Histograms in Figure 4 show the distribution of limestone hill sizes for three different series of intervals. The histogram is strongly skewed to the left. Around 90% of the limestone hills in Peninsular Malaysia are smaller than 1 km^2. There are only three hills larger than 10 km^2, namely, Prs 64 Wang Ulu – 85.30 km^2, Ktn 176 Batu Baloh – 21.2 km^2, and Phg 77 Bukit Mengapur – 11.8 km^2. Another 17 hills range in size from 2 km^2 – 10 km^2, and 22 hills are 1 km^2 – 2 km^2 big. Around 60 % of the hills are smaller than 0.1 km^2 and a further 14 % are smaller than 0.01 km^2.

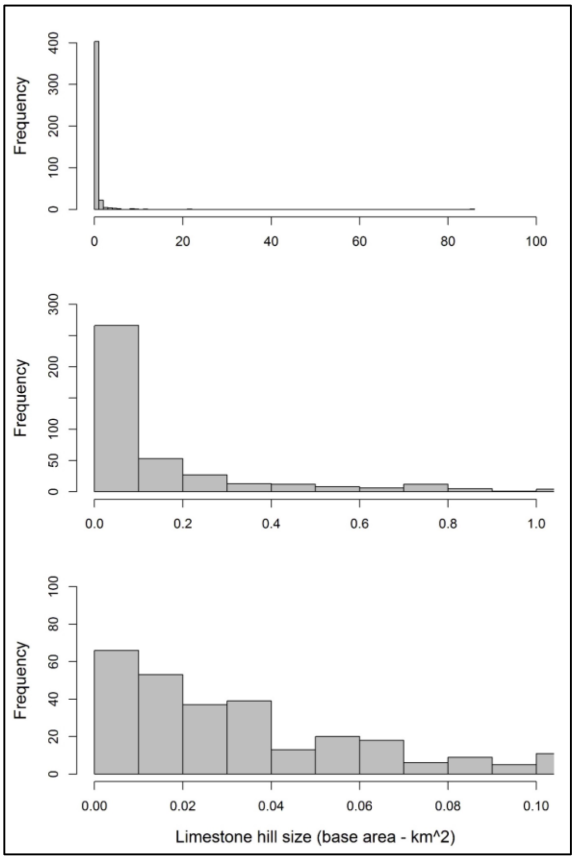

Fig. 4. Histograms show the distribution of the size of limestone hills in Peninsular Malaysia. (A) Histogram of all 445 hills with bin's size of 1 km^2. (B) Histogram of those hills smaller than 1 km^2 with bin's size of 0.1 km^2. (C) Histogram of those hills smaller than 0.1 km^2 with bin's size of 0.01 km^2.

Figure 5 shows the distribution of the degree of isolation for each hill in three different spatial contexts. More than half (62%) of the hills were within 10 km of seven others. The most isolated ones for each spatial context are shown in Table 1. There were two extremely isolated hills each of the three contexts with only single hills within 10 km, 25 km, and 50 km radiuses, namely "mykarst-034" and "mykarst-057". In addition, density maps of a 10 km search radius indicated that there were 22 limestone clusters relatively isolated from the other hills (i.e. at least 10 km from the nearest cluster), and 15 of these clusters comprised fewer than 5 hills (Fig. 6).

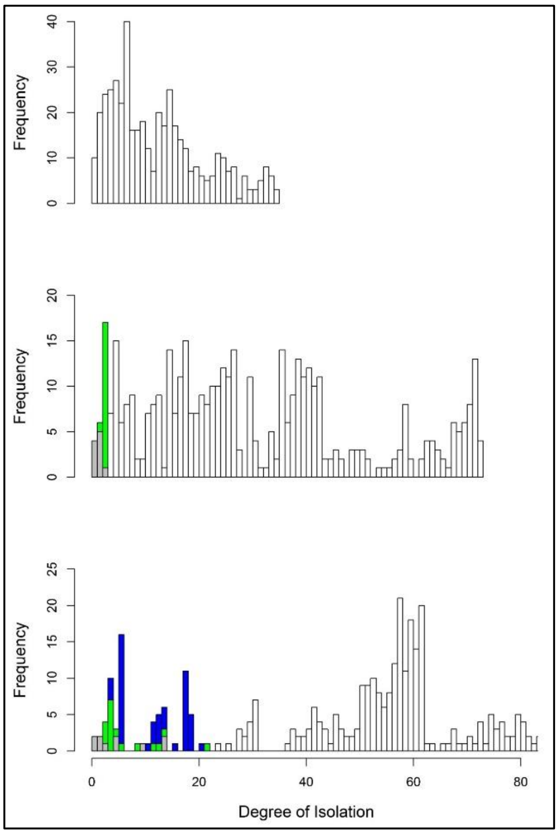

Fig. 5. Histograms show the degree of isolation (i.e. density values) in three different geographical contexts: (A) Number of adjacent hills within 10 km radius of each hill. (B) Number of adjacent hills within 25 km radius of each hill. (C) Number of adjacent hills within 50 km radius of each hill.

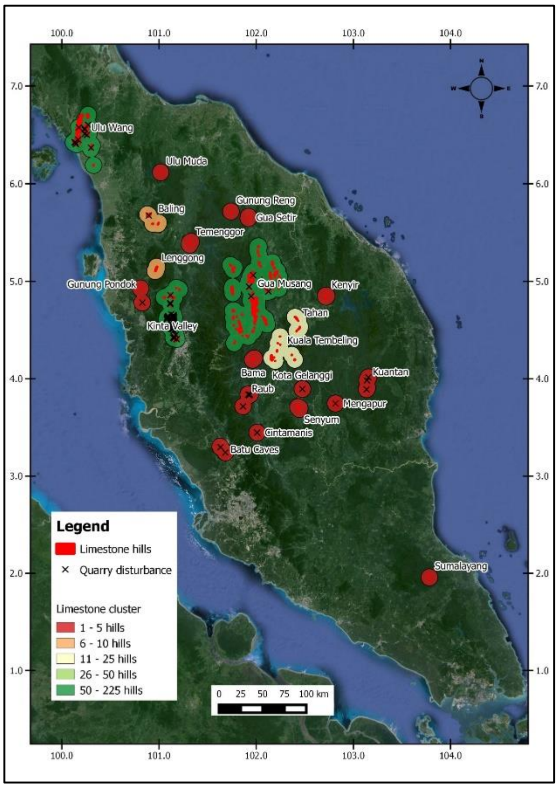

Fig. 6. Map of limestone hills clusters in Peninsular Malaysia shows that number of limestone hills and the quarrying activities in each cluster. Imagery ©2016 Data SIO, NOAA, U.S. Mavy, NGA, GEBCO, Landsat, Map data ©2016 Google

Table 1. Top isolated 40 limestone hills in Peninsular Malaysia.

No.	Name	Degree of Isolation (Heatmap analysis)			Quarrying sign
		10 km radius	25 km radius	50 km radius	
1	mykarst-034	1.0	1.0	1.0	No
2	mykarst-057	1.0	1.0	1.0	No
3	Phg 05 Bt. Cintamanis	1.0	1.0	1.5	Yes
4	Phg 77 Bukit Mengapur	1.0	1.0	1.6	Yes
5	Ktn 01 G. Reng	1.0	1.1	2.3	No
6	Sgr 01 Batu Caves	1.1	2.5	2.9	Yes
7	Sgr 02 Bukit Takun	2.0	2.7	2.9	No
8	Sgr 03 Bukit Anak Takun	2.1	2.8	3.0	Yes
9	mykarst-170	2.6	2.9	3.1	No
10	mykarst-172	2.6	2.9	3.2	No
11	mykarst-171	2.8	3.0	3.2	No
12	mykarst-072	2.9	3.0	3.3	No
13	Trg 01 Bukit Bewah	2.9	3.0	3.4	No
14	Trg 02 B. Taat	2.9	3.0	3.5	No
15	Phg 75 Bt Tenggek	1.7	3.0	3.7	Yes
16	Phg 74 Bt Sagu	1.8	3.4	3.9	Yes
17	Phg 72 Bt Panching	1.9	3.1	3.9	Yes
18	Phg 73 Bt Charas	2.0	3.4	3.9	No
19	mykarst-065	1.0	2.5	4.5	Yes
20	Phg 01 Kota Gelanggi	1.0	1.1	4.5	Yes
21	Ktn 02 Gua Setir	1.9	2.1	4.5	No
22	Phg 08 G. Panas	3.8	4.3	5.0	Yes
23	mykarst-173	3.9	4.4	5.0	Yes
24	Phg 06 Bt Serdam 06	3.8	4.4	5.0	Yes
25	Phg 07 Gua Kechil	3.9	4.4	5.0	No
26	mykarst-184	1.9	2.0	5.1	No
27	Kdh 02 G. Pulai	1.9	3.4	5.2	No
28	Kdh 01 Bt Baling	1.9	3.9	5.4	Yes
29	mykarst-079	4.8	5.0	5.7	No
30	Phg 04 Bt Terus	4.8	5.0	5.7	No
31	Phg 02 G. Senyum	4.5	5.0	5.7	No
32	mykarst-085	1.9	4.8	5.7	No
33	mykarst-150	4.9	5.0	5.7	No
34	Phg 03 Bt. Jebak Puyoh	4.8	5.0	5.7	No
35	mykarst-084	3.3	4.6	5.7	No
36	mykarst-082	3.1	4.6	5.7	No
37	mykarst-083	3.2	4.6	5.7	No
38	mykarst-038	1.3	1.9	8.7	No
39	Prk 59 Bt. Batu Kurau	1.0	1.3	9.4	No
40	mykarst-098	2.2	4.4	10.3	No

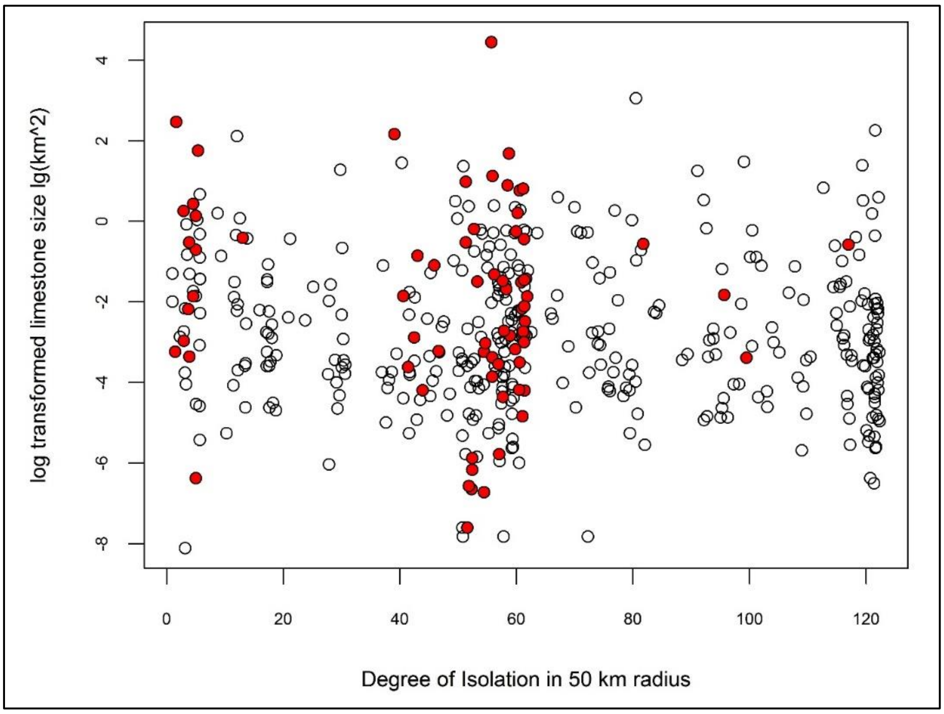

Fig. 7. Size and degree of isolation of limestone hills in the general context of Peninsular Malaysia. Red closed circles indicate hills with quarrying disturbance.

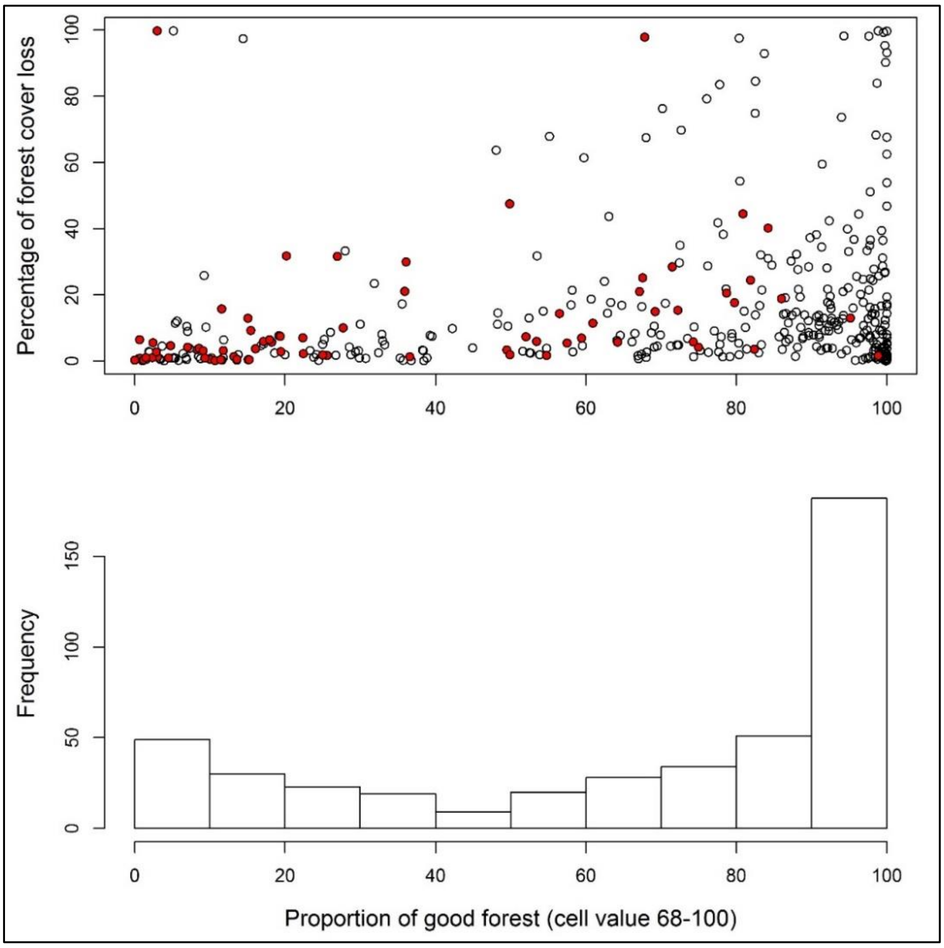

Fig. 8. Forest status in buffer zone. (Top) Proportion of forest with cover value (68-100) in year 2000 and percentage of forest loss from year 2000 – 2014 in the buffer zone of each limestone hill. Red closed circles are the hills with quarrying disturbance. (Bottom) Histogram of the proportion of forest cover value (68-100) remains in the buffer zone of all the limestone in Peninsular Malaysia.

Threat parameters of limestone hills

A total of 73 of 445 limestone hills (16%) in Peninsular Malaysia have signs of operational or historical quarrying activities (Fig. 6 and 7). There was at least one hill completely quarried away – "Phg 72 Bt Panching". It appears there is no clear association between the threat of quarrying and limestone physical parameters (Fig. 7).

In terms of buffer zone status, half of the limestone hills appeared to have good forest coverage (i.e. more than 80 % of the buffer zone still had a forest coverage value above 67; Fig. 8). About 10% of the limestone hills had buffer zone forests that were highly degraded (i.e. each with more than 80 % of the buffer zone having a forest coverage value below 34).

Discussion

Our GIS database, which consists of 445 limestone hills marked on Google Earth with their names and reference sources, is the first up-to-date, comprehensive and accessible source for limestone hills in Peninsula Malaysia and possibly in the tropics.

Many of the limestone hills were previously recorded by several different researchers, while about one fifth of the hills were recorded only once. Our records, however, require further ground verification, especially for hills that were previously recorded only once. As already noted by Davison and Kiew [34] and Price [16], the exact number of limestone hills is difficult to determine due to the ambiguous definition of a single hill. We define a single hill as one that is completely separated from nearby hills aboveground for at least 10 m and has a size of at least 0.0001 km^2. There were hills that had previously been recorded that we did not include in our database due to a lack of certainty; for example, we recorded 149 hills in the state of Kelantan, whereas, Davison and Kiew [34] estimated 210 and verified 120 of them; and Price [16] recorded 234 hills. Nevertheless, we believe our GIS database will be the first reference point for future verification. Furthermore, the analytical workflow that we used in this study can be replicated to generate up-to-date databases when new hills are found or data regarding new forest cover layers become available in the future.

We suggest that the reference code we assigned to each limestone hill be used by future users when they report their findings regarding individual hills. Previously, biodiversity sampling has usually cited the name of a limestone hill along with GPS coordinates. However, there have been incidents of inconsistent use of limestone hill names, which can create confusion especially when the reference source of the hill name is not provided. In addition, GPS coordinates taken by different users with different datum can result in discrepancies of tens or hundreds of meters, which can be an issue when there are many hills in close proximity to each another. Most importantly, the inconsistent use of hill names and coordinates can hinder the sharing and integration of information from diverse scientific publications. Hence, we hope this database will be a reference platform for information collected from limestone hills throughout Peninsular Malaysia.

Some aspects of biodiversity have been documented for a number of limestone hills in Peninsular Malaysia [8, 9, 34-38]. Almost all of these biodiversity data were published as texts. Hence, integration of these data from various publications cannot be easily achieved as the data can only be extracted and verified manually. Wherever possible, we suggest that biodiversity locality data should be published in KML or another GIS vector data format. For example, taxonomy and location information can utilize the Google Earth Spreadsheet Mapper v3.0 (http://www.google.com/earth/outreach/tutorials/spreadsheet3.html) as described by Liew et al. [9]. By using the limestone database that we established, these biodiversity data in GIS format can be easily retrieved using GIS geoprocessing and analysis applications.

Limestone hill physical parameters
Limestone hills in the tropics are considered de facto islands as they are surrounded by non-calcareous substrata [35]. Hence, the biodiversity richness and endemism patterns on these hills are, on the whole, shaped by the same ecological and evolutionary processes as on islands. Two main island characteristics, size and isolation, have been shown to be the main determinants of endemism and geographically structured genetic patterns for species on limestone hills [13, 35, 39-41].

Our database indicates that the majority of hills in Peninsular Malaysia are smaller than 0.1 km^2. A quarter are smaller than a football field (0.01 km^2). Currently, very little is known about these small hills and the minimum size required to support significant levels of biodiversity. This information gap needs urgently to be filled before important management decisions can be made regarding their 'irreplaceability'. When such information is available, for example, a threshold line can be plotted in Figure 7 to determine conservation and research priorities based on the size and isolation of limestone hills in the general context of Peninsular Malaysia's limestone hills.

Limestone hill isolation can be assessed from the aspect of a single hill, or a cluster that consists of a number of hills. Such information is very important as it is not easy to formulate a management plan for all 445 hills in Peninsular Malaysia at this moment. One way to address this issue is to group these unevenly scattered hills into a number of manageable working clusters using systematic quantitative and qualitative approaches. In this study, we identified the clusters based on the degree of isolation when a group of hills was less than 10 km apart and, at the same time, the cluster was approximately 10 km away from other limestone clusters. Nevertheless, the limestone hill clusters identified by this approach need to be refined with an integrated and systematic approach using quantitative and qualitative information regarding their geological formation, extent of cave networks, biodiversity and biogeography.

When this is done, a more coordinated and rigorous research and conservation program can be designed within a limestone cluster or between clusters. A limestone cluster could consist of a number of lenticular hills that are not on a single bedrock or a number of hills that are on the same limestone bedrock. Hence, a number of limestone hills can be grounded in a limestone cluster, just like a number of islands can be grouped as an archipelago. Even high-level conservation decisions, such as the process of nomination and inscription of limestone hills for world heritage, has been done ad hoc, which has led to a suboptimal representation of the limestone hill values without considering the 'irreplaceability' of these hills in the overall context of hills in a region [5].

Limestone hill threat parameters
Only a few limestone clusters in Malaysia have been accredited World Heritage status, namely, Mulu (Sarawak), Niah (Sarawak), and Lenggong (Perak). In addition, there are a few more clusters that have been protected as part of a National Park, such as the Langkawi Islands, and those in Kuala Tahan, Kuala Tembeling and Kenyir. However, the majority of limestone hills in Malaysia do not have protected area status and are vulnerable to anthropogenic disturbances.

Generally, limestone hills have sparse vegetation cover, especially for small hills that have thin soil layers. This type of habitat is extremely sensitive to anthropogenic disturbances such as deforestation and quarrying [13, 35, 42-43]. In addition to the size and isolation factors mentioned above, degradation of the forest and quarrying could change the biodiversity pattern and genetic structures of the organisms living on limestone hills [11, 44].

One immediate management intervention is to preserve a wide forested buffer zone around the base of the hills [11, 13, 34]. Davison and Kiew [34] suggested a forested buffer zone of at least 200 m around a hill to prevent burning, to provide shaded habitat and to protect the stream system. Our analysis of buffer zone forest status suggests that most of the forest in the buffer zones was still in reasonably good condition in the year 2000, with relatively low forest cover loss in the past decade. However, as mature oil palm plantations also have high forest cover values in Hansen et al. [26], it is possible that the forest cover in the buffer zones of many limestone hills in our analysis could actually be oil palm plantations, and this analysis needs to be repeated when better forest cover data is available in the future.

We found that many of the limestone hills with very poor forest conditions in buffer zones have been quarried. Compared to deforestation, quarrying is more destructive and its impact is irreversible [7]. The most common practice in the industry is to completely quarry away a limestone hill and then move on to the adjacent hills. It seems that there has not been a dramatic increase in the number of quarries operating – Price [16] reported a total of 62 limestones quarries in 1975 and at the time of our research we detected 73. However, the main cause for concern is that ongoing quarrying activities are occurring in seven of the highly isolated and small (< 5 hills) clusters, namely, Raub, Gunung Pondok, Mengapur, and Kuantan (Figure 6). The companies mining these extremely vulnerable hills should be engaged with urgently in order to develop biodiversity and conservation plans.

Implications for conservation

The current version of our database should be seen as a first reference point to provide quantitative and qualitative information regarding limestone hills in Peninsular Malaysia that users can access and build upon (e.g. [45]). We acknowledge that our data lacked rigorous enough ground-checking for the map to be considered final: there are many hills that require further verification. Nevertheless, limestone hills in different states within Peninsular Malaysia can now be prioritized for conservation through systematic conservation planning [46] by using our physical and threat parameters as signifiers of their ‘irreplaceability’ and ‘vulnerability’, respectively. We hope that this user-friendly karst database can better facilitate the communication and sharing of spatial information, especially among ordinary citizens, to raise awareness and concern for the natural environment [47]. Furthermore, we hope our database will encourage stakeholders of the limestone hills, including scientists, industries and policy-makers, to enrich the database with more data documenting their archaeological, speleological, geological, biodiversity, cultural, and economic importance.

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References

[1] Myers, N., Mittermeier, R. A., Mittermeier, C. G., Da Fonseca, G. A., and Kent, J. 2000. Biodiversity hotspots for conservation priorities. *Nature* 403(6772):853-858.

[2] Brooks, T. M., Mittermeier, R. A., da Fonseca, G. A., Gerlach, J., Hoffmann, M., Lamoreux, J. F., Mittermeier, C. G., and Rodrigues, A. S. 2006. Global biodiversity conservation priorities. *Science* 313(5783):58-61.

[3] Olson, D. M., Dinerstein, E., Wikramanayake, E. D., Burgess, N. D., Powell, G. V., Underwood, E. C., D'amico, J. A., Itoua, I., Strand, H. E., Morrison, J. C., Loucks, C. J., Allnutt, T. F., Ricketts, T. H., Kura,

Y., Lamoreux, J. F., Wettengel, W. W., Hedao, P., and Kassem, K. R. 2001. Terrestrial ecoregions of the world: a new map of life on earth. *BioScience* 51(11):933-938.

[4] Naidoo, R., Balmford, A., Costanza, R., Fisher, B., Green, R. E., Lehner, B., Malcolm, T. R., and Ricketts, T. H. 2008. *Global mapping of ecosystem services and conservation priorities.* Proceedings of the National Academy of Sciences 105(28):9495-9500.

[5] Williams, P. 2008. *World heritage caves and karst.* IUCN, Gland, Switzerland*,* 57.

[6] Schilthuizen, M. 2004. Land snail conservation in Borneo: limestone outcrops act as arks. *Journal of Conchology* Special Publication 3:149-154.

[7] Clements, R., Sodhi, N. S., Schilthuizen, M., and Ng, P. K. 2006. Limestone karsts of Southeast Asia: imperiled arks of biodiversity. *Bioscience* 56(9):733-742.

[8] Chua, L. S. L., Kiew, R., and Chan, Y. M. 2009. Assessing conservation status of Peninsular Malaysian Begonias (Begoniaceae). *Blumea-Biodiversity, Evolution and Biogeography of Plants* 54(1-3):94-98.

[9] Liew, T. S., Vermeulen, J. J., bin Marzuki, M. E., and Schilthuizen, M. 2014. A cybertaxonomic revision of the micro-landsnail genus Plectostoma Adam (Mollusca, Caenogastropoda, Diplommatinidae), from Peninsular Malaysia, Sumatra and Indochina. *ZooKeys* 393:1-109.

[10] Schilthuizen, M., and Clements, R. (2008). Tracking extinction from space. *Tentacle* 16:8-9.

[11] Schilthuizen, M., Liew , T. S., Elahan, B. B., and Lackman-Ancrenaz, I. 2005. Effects of karst forest degradation on pulmonate and prosobranch land snail communities in Sabah, Malaysian Borneo. *Conservation Biology* 19(3):949-954.

[12] Liew, T.S. 2015. *Plectostoma sciaphilum*. The IUCN Red List of Threatened Species 2015: e.T168180A77504770. http://dx.doi.org/10.2305/IUCN.UK.2015-1.RLTS.T168180A77504770.en. Downloaded 21 December 2015.

[13] Vermeulen, J., and Whitten, T. 1999. *Biodiversity and cultural property in the management of limestone resources*. World Bank, Washington, DC, 120.

[14] Hussain, Z., Zakaria, M. R., and Leman, M. L. 2008. Geoheritage of Malaysia. In: *Geoheritage of East and Southeast Asia*. Leman, M. S., Reedman, A. and Chen, S. P. (Eds.),149-184. Amang Press Sdn. Bhd, for LESTARI, Universiti Kebangsaan Malaysia.

[15] Paton, J. R. 1961. A brief account of the geology of the limestone hills of Malaya. *Bull Raffles Mus* 26:66-75.

[16] Price, L. 2001. *Caves and karst of Peninsular Malaysia: a register.* Gua Publications.

[17] Price, L. 2015. *Caves and karst of Peninsular Malaysia*. *A Register*. 2nd Edition. Berliner Höhlenkunliche Berichte Volume 54. Speläclub Berlin.

[18] de Carvalho, O. A., Guimarães, R. F., Montgomery, D. R., Gillespie, A. R., Trancoso Gomes, R. A., de Souza Martins, É., and Silva, N. C. 2013. Karst depression detection using ASTER, ALOS/PRISM and SRTM-Derived Digital Elevation Models in the Bambuí Group, Brazil. *Remote Sensing* 6(1):330-351.

[19] Theilen-Willige, B., Malek, H. A., Charif, A., El Bchari, F., and Chaïbi, M. 2014. Remote sensing and GIS contribution to the investigation of karst landscapes in NW-Morocco. *Geosciences* 4(2):50-72.

[20] Kobal, M., Bertoncelj, I., Pirotti, F., Dakskobler, I., and Kutnar, L. 2015. Using Lidar data to analyse sinkhole characteristics relevant for understory vegetation under forest cover-case study of a high karst area in the Dinaric Mountains. *PloS one* 10(3):e0122070.

[21] Siart, C., Bubenzer, O., and Eitel, B. 2009. Combining digital elevation data (SRTM/ASTER), high resolution satellite imagery (Quickbird) and GIS for geomorphological mapping: a multi-component case study on Mediterranean karst in Central Crete. *Geomorphology* 112(1):106-121.

[22] Rajendran, S., and Nasir, S. 2014. ASTER mapping of limestone formations and study of caves, springs and depressions in parts of Sultanate of Oman. *Environmental Earth Sciences* 71(1):133-146.

[23] QGIS Development Team. 2015. *QGIS Geographic Information System.* Open Source Geospatial Foundation Project. http://qgis.osgeo.org

[24] Conrad, O., Bechtel, B., Bock, M., Dietrich, H., Fischer, E., Gerlitz, L., Wehberg, J., Wichmann, V., and Böhner, J. 2015. *System for automated geoscientific analyses (SAGA) v. 2.1.4, geoscientific model development, 8, 1991-2007*, doi:10.5194/gmd-8-1991-201.

[25] R Core Team. 2015. *R: a language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria.* Available at http://www.R-project.org/

[26] Hansen, M. C., Potapov, P. V., Moore, R., Hancher, M., Turubanova, S. A., Tyukavina, A., Thau, D., Stehman, SV., Goetz, SJ., Loveland, TR., Kommareddy, A., Egorov, A., Chini, L., Justice, CO., and Townshend, J. R. G. 2013. High-resolution global maps of 21st-century forest cover change. *Science* 342(6160):850-853.

[27] Miettinen, J., Shi, C., Tan, W. J., and Liew, S. C. 2012. 2010 land cover map of insular Southeast Asia in 250-m spatial resolution. *Remote Sensing Letters* 3(1):11-20.

[28] Shimada, M., Itoh, T., Motooka, T., Watanabe, M., Shiraishi, T., Thapa, R., and Lucas, R. 2014. New global forest/non-forest maps from ALOS PALSAR data (2007–2010). *Remote Sensing of Environment* 155:13-31.

[29] Dong, J., Xiao, X., Sheldon, S., Biradar, C., Duong, N. D., and Hazarika, M. 2012. A comparison of forest cover maps in Mainland Southeast Asia from multiple sources: PALSAR, MERIS, MODIS and FRA. *Remote Sensing of Environment* 127: 60-73.

[30] Tropek, R., Sedláček, O., Beck, J., Keil, P., Musilová, Z., Šímová, I., and Storch, D. (2014). Comment on “high-resolution global maps of 21st-century forest cover change”. *Science* 344(6187):981-981.

[31] Hijmans R. J. 2015. *Raster: geographic data analysis and modeling.* R package version 2.5-2. http://CRAN.R-project.org/package=raster

[32] Bivand R., Keitt T. and Rowlingson B. 2015. *Rgdal: bindings for the geospatial data.* Abstraction Library. R package version 1.1-3. http://CRAN.R-project.org/package=rgdal

[33] Bivand R. and Rundel C. 2015. *Rgeos: interface to geometry engine - open source (GEOS)*. R package version 0.3-15. http://CRAN.R-project.org/package=rgeos

[34] Davison G. W. H. and Kiew R. 1990. *Survey of flora and fauna of limestone hills in Kelantan, with recommendations for conservation.* Kuala Lumpur, Worldwide Fund for Nature Malaysia.

[35] Clements, R., Ng, P. K., Lu, X. X., Ambu, S., Schilthuizen, M., and Bradshaw, C. J. 2008. Using biogeographical patterns of endemic land snails to improve conservation planning for limestone karsts. *Biological conservation* 141(11):2751-2764.

[36] Chin, S. C. 1977. The limestone hill flora of Malaya I. *Gardens' Bulletin Singapore* 30:165-219.

[37] Chin, S. C. 1979. The limestone hill flora of Malaya II. *Gardens' Bulletin Singapore* 32:64-203.

[38] Chin, S. C. 1983. The limestone hill flora of Malaya III. *Gardens' Bulletin Singapore* 35:137-190.

[39] Latinne, A., Waengsothorn, S., Rojanadilok, P., Eiamampai, K., Sribuarod, K., and Michaux, J. R. 2012. Combined mitochondrial and nuclear markers revealed a deep vicariant history for Leopoldamys neilli, a cave-dwelling rodent of Thailand. *PloS One* 7(10): e47670.

[40] Haskell, D. G., and Pan, J. W. 2013. Phylogenetic analysis of threatened and range-restricted limestone specialists in the land snail genus Anguispira. *Conservation Genetics* 14(3):671-682.

[41] Gao, Y., Ai, B., Kong, H., Kang, M., and Huang, H. 2015. Geographical pattern of isolation and diversification in karst habitat islands: a case study in the Primulina eburnea complex. *Journal of Biogeography* 42(11):2131-2144.

[42] Tuyet, D. 2001. Characteristics of karst ecosystems of Vietnam and their vulnerability to human impact. *Acta Geologica Sinica* (English Edition) 75(3):325-329.

[43] Zhang, J., Chen, H., Su, Y., Shi, Y., Zhang, W., and Kong, X. 2011. Spatial variability of surface soil moisture in a depression area of karst region. *Clean–Soil, Air, Water* 39(7):619-625.

[44] Flavenot, T., Fellous, S., Abdelkrim, J., Baguette, M., and Coulon, A. 2015. Impact of quarrying on genetic diversity an approach across landscapes and over time. *Conservation Genetics* 16(1):181-194.

[45] Foody, G. M. 2014. Rating crowdsourced annotations: evaluating contributions of variable quality and completeness. *International Journal of Digital Earth* 7(8):650-670.

[46] Margules, C. R., and Pressey, R. L. 2000. Systematic conservation planning. *Nature* 405(6783): 243-253.

[47] Butler, D. 2006. Virtual globes: the web-wide world. *Nature* 439:776–778.

Supplemental Information

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Supplemental Information 1. References used in digitalisation of limestone hills.
Supplemental Information 2. Limestone hills GIS file (KML format).
Supplemental Information 3. GIS data and R script for data analysis.