DIRECTIONS IN DEVELOPMENT

Biodiversity and Cultural Property in the Management of Limestone Resources

Lessons from East Asia

JAAP VERMEULEN AND TONY WHITTEN

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Foreword

As East Asia pulls itself from the grips of a major financial crisis, environmental managers and planners have an opportunity to better integrate environmental concerns with their governments' long-term development goals. The World Bank is working with its clients to facilitate this process, and to help them shift their growth paradigms toward more environmentally sustainable development.

Limestone is found in all East Asian countries, and cement, the chief limestone product, is a common barometer of economic progress. Many World Bank-financed infrastructure projects use cement, often in considerable quantities, and are subject to careful screening to ensure compliance with the World Bank's environmental safeguard policies. Until now, the focus of the impact assessments has been on the immediate project area, or, when cement factories themselves are scrutinized, on the dust and noise emitted by the plants. Today, however, the perspectives have changed and we look at the broader "area of influence" of the project, and, as this report shows, there is more than dust and noise requiring attention.

Environmental assessments have generally overlooked the impact of projects on the limestone-source areas. Limestone regions are remarkable for both their highly characteristic biodiversity and their importance as ancient and modern cultural heritage sites. Elements of these biological and cultural resources have considerable economic value, particularly at the local level. By ignoring these characteristics, development activities have directly and indirectly eliminated species and cultural sites, even when this could have been avoided had relatively simple preventive steps been taken. The report draws attention to two key aspects of limestone resource management that could help minimize impacts: (i) the selection of an appropriate site for exploitation, and (ii) the management of selected sites during and after quarrying. For example, sites already disturbed, without caves, or in a large connected area of limestone should be favored, and rational exploitation strategies should be developed within the context of regional inventories and assessments of limestone resources. In addition, during and after quarrying, there exists a range of management options, from reducing blasting impacts to restoring sites, that can recapture many of the original values.

Through a wide distribution of this report among the various stakeholders—infrastructure engineers, environmental assessment professionals, biodiversity specialists, archaeologists and other cultural property specialists—the future management of limestone resources of East Asia would receive much needed attention.

I am very pleased that IUCN—The World Conservation Union has collaborated closely with us during the preparation of this report.

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Sector Manager
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Note: An annotated set of maps at a scale of 1:1,000,000 (1:4,000,000 for China) showing limestone outcrops in East Asia will be available in late 1999. For details please contact Tony Whitten on +1-202-522-7147, twhitten@worldbank.org.

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* The World Bank contracted the Rijksherbarium-Hortus Botanicus in Leiden, the Netherlands, to produce this report, and Dr. Jaap Vermeulen was hired as the lead consultant. The necessary funding was acquired from World Bank trust funds from the governments of the Netherlands, Switzerland, Sweden, and France. A team of specialists was engaged by the lead consultant to compile relevant information on the location, status, and management of biodiversity and cultural property in limestone areas of East Asia. All prepared reports for their particular field of specialization. These reports were synthesised into a draft, which formed the focus for a workshop in Bangkok in January 1999 that was attended by members of the team and other interested individuals, including cement engineers, from East Asia and elsewhere. The Hanoi and Bangkok offices of IUCN–The World Conservation Union were hired to organize this meeting.

Summary

Limestone is an extremely important raw material and is one of the most versatile of all industrial rocks and minerals. The main use of this nonrenewable resource is in the construction industry as an essential raw material for cement manufacture, as crushed rock aggregate, and also as a source of building and ornamental stone. It is relatively cheap, can be used in a wide variety of ways, and occurs in many countries. Limestone is of major importance in development, with the production of cement even used as a barometer of growth and progress. In many infrastructure projects—such as dam and bridge construction, port development, building construction, and road building and upgrading—the extraction of limestone is a fundamental, and in most cases irreplaceable, development activity.

The quarrying of limestone, being a subsidiary (and often remote) element of a large infrastructure project, is rarely adequately assessed for its total impacts. Even environmental assessments for large cement factories fail to take into account potentially unique biological, cultural, geological, and scenic features. The raising of awareness of the importance of these features forms the core of this report.

Three World Bank Operational Policies apply to the impacts of limestone quarrying; yet an analysis of a sample of environmental assessments submitted to the World Bank (including the International Finance Corporation) as part of the preparation of infrastructure and cement factory investments revealed that the special nature and concern of limestone areas with respect to biodiversity and cultural property were not taken into account.

The biodiversity of limestone ecosystems, both surface and cave systems, is highly characteristic and restricted, comprising species able to cope with the highly alkaline environment due to the abundance of calcium carbonate, species that can endure the severity of exceedingly dry soil conditions over part of the year, and species confined to, or found primarily in, limestone caves. Some are confined to single hills or cave systems. Many of the species concerned are relatively small, little known,

and are rarely included in lists of protected species, which tend to focus on the larger and more conspicuous species. Extinctions of limestone-restricted species as a result of economic development have already been recorded, and the status of other species is perilous.

Some of the species concerned, for instance cave-nesting swiftlets, have a significant economic value, their nests being an extremely valuable commodity used in oriental delicacies—weight for weight more valuable than gold. Other species are equally important in an economic sense but in a less obvious way. Bats, for example, are important pollinators of various commercial tree crops and major predators on damaging or dangerous insects. Certain plants, notably slipper orchids and cycads, are commercially extremely valuable, but their rate of harvest is rarely sustainable.

Certain limestone areas are also significant in that they harbor some of the earliest evidences of human culture in East Asia, and in some countries they are historically significant in having sheltered revolutionary movements. Paleontological remains in cave deposits have provided great insights into prehistoric fauna. In the humid tropics, caves are among the very few sites where ancient organic material is preserved. Geological remains provide invaluable information about past environmental conditions, including climate. Also, many karst areas are regarded as being exceptionally beautiful, have cultural and geological value, and attract large numbers of tourists.

Sites for limestone exploitation should:

- be located in limestone deposits that have already been affected by other use, or by accidents
- be dolomitic limestone, limestone with limited karstification, or both (if the criteria for the intended use are met)
- be located in the largest limestone areas and leave a substantial part of the areas untouched
- avoid isolated limestone hills (remote from other limestone hills) because such hills are usually rich in site-endemic species
- be located where one large quarry affecting part of a limestone area can replace a number of small quarries throughout the area
- be at the foot of limestone massifs to avoid unnecessary damage
- avoid sites with caves, small voids, and underground streams and springs

- be placed to control sedimentation in stream and local drainage systems.

Quarrying limestone affects the integrity of natural and cultural values of karst areas through dust, blasting shock, changes in hydrology, water pollution, and collateral damage. Other general threats include water extraction, bush fires, excessive exploitation of birds' nests and guano, uncontrolled tourism, hunting, and overextraction of timber and nontimber forest products.

These topics must be dealt with adequately in environmental assessments by competent consultants with adequate time to perform the comprehensive analysis required by the World Bank. The examination of issues by a qualified generalist would be a useful first step.

Disused quarries or road cuts should be restored by:

- remodeling perpendicular slopes to avoid uncontrolled collapse and facilitate regeneration of the vegetation cover
- loosening the quarry floor that has been compressed and hardened by the use of heavy machinery
- ensuring sufficient drainage of the quarry floor
- refilling crevices and holes of reconstructed gentle slopes with soil
- replanting the area with native plant species, with limited use of artificial fertilizers and with no pesticides
- removing wreckage, buildings, engines, and so forth
- monitoring the regeneration.

In some cases, reclaimed quarries can be used as recreation parks, exploited as fish ponds or water reservoirs, or exploited as tourist attractions.

Countries with limestone resources should make systematic inventories of them and collect data on their characteristics, including biodiversity, cultural, geological, and aesthetic properties, so that the resources are exploited in a rational and sustainable manner.Where relevant, animal and plant species of limestone habitats should be listed as protected species.

The Clean Development Mechanism (CDM) could offer an opportunity for modernization of the local cement industry, and with appropriate influence applied, a small part of the financial gains could be applied for national limestone resource surveys, including biodiversity and cultural property.

1

Background and Policy Context

There is an enormous demand in East Asia for both housing and other building construction, and for the development of infrastructure for transport, water, and other utility provision. At the very foundation of all this activity, there is a burgeoning demand for limestone, particularly by the construction industries. This involves cement production, as well as supply of lime, aggregates, building stone, and other varied products.

Traditional quarrying practice is based on small-scale, highly labor-intensive, localized extraction enterprises. Although this may well continue for the localized supply of aggregates and agricultural demand, it is no longer appropriate or even feasible to meet the needs of the cement industry in this way. At an intermediate level, medium-sized (and under-capitalized) cement manufacturing may develop. This level of operation is an inevitable stage in the development process and, regrettably, leads to major issues of habitat destruction, degradation of landscape, dust, and other problems. As larger-scale and more technologically advanced manufacturing develops, some of the medium-sized plants may revert to supplying aggregates, and others will eventually close. Again, as a result of undercapitalization, there is no capacity for rehabilitation of former quarries and other sites.

The future of the cement industry lies the hands of major corporations, either government-owned, privately owned with indigenous capital, or privately owned with international capital input. These corporations are able to provide the necessary scale of operation to use state-of-the-art technology in both quarrying and manufacturing and thus to minimize destructive impacts on the environment. They are also able to use intensive exploitation of confined areas rather than widespread and diffuse extraction, with its more widespread impacts. The cement industry today is one where “bigger is better.”

The localized extraction of limestone for aggregate and lime-burning will doubtless continue. Although small in scale, these industries can cause significant environmental impacts. However, with increasing awareness of, and education in, environmental issues, agreed codes of practice and integration into local-regional planning, controls will evolve and in turn minimize these more diffuse impacts.

Coverage

The main concerns in this report are biodiversity[1] and cultural property associated with limestone in East Asia. These areas of interest are rarely paired, but do have common features: both are largely untraded goods, although some elements are highly valued by some but not by others. The World Bank finds that their loss or damage in the course of economic development is a significant issue, and that limestone areas are very important sites for both biodiversity and cultural property.

Other limestone-related issues are dealt with relatively briefly insofar as they are relevant to the purpose of the report. In this way, the report is a first step to redress the balance in favor of concern for limestone biodiversity and cultural property, which are under-represented in the literature on limestone. Although such topics karst formation, karst features, hydrology, and geological features are discussed only very briefly, no lack of their importance is implied.

This report deals primarily with limestone areas in East Asia, which in World Bank parlance comprises its client countries of Mongolia, China, the Republic of Korea, Thailand, the Lao People's Democratic Republic (Lao PDR), Vietnam, Cambodia, Malaysia, the Philippines, Indonesia, and Papua New Guinea. Many of the conclusions and recommendations are nonetheless applicable to tropical and subtropical karst areas worldwide.

Mainstreaming Biodiversity

At the 1995 Conference of the Parties to the Convention on Biological Diversity, the World Bank launched a significant document entitled Mainstreaming Biodiversity in Development. The foreword states: "The challenge now is for the Bank to help its developing country partners to mainstream biodiversity conservation in environmentally sustainable development. Investment operations in traditional sectors such as agriculture, forestry, energy, tourism, and urban and infrastructure development should gradually become more 'biodiversity friendly.'" This report highlights an aspect of biodiversity that is severely threatened, is potentially affected by a range of infrastructure projects, and has until now received almost no attention.

Environmental Assessment Review

Fifteen environmental assessments of World Bank and International Finance Corporation (IFC) projects from the last 10 years involving major infrastructure and cement factory investments were reviewed. None of the assessments mentions the unique aspects of limestone biodiversity, adequately addresses biodiversity issues, or proposes measures to mitigate and monitor the impact on local biodiversity. However, one report mentions the aesthetic and wilderness values of the limestone areas that would be affected by the project. There was no indication that cultural remains or values related to limestone were assessed.

World Bank Policies

The conservation of natural habitats is essential for long-term sustainable development. The World Bank therefore supports the protection, maintenance, and rehabilitation of natural habitats and their functions in its economic and sector work, project financing, and policy dialogue. The Bank supports and expects borrowers to apply a precautionary approach to natural resource management to ensure opportunities for environmentally sustainable development. There are three World Bank Operational Policies of direct relevance to the impacts of limestone quarrying: OP 4.01 on Environmental Assessment, OP 4.04 on Natural Habitats, and Operational Policy Note (OPN) 11.03 (draft OP 4.11) on Safeguarding Cultural Property in Bank Financed Projects.

Environmental Assessment. This cornerstone policy clarifies that the "Bank requires environmental assessment (EA) of projects proposed for Bank financing to help ensure that they are environmentally sound and sustainable, and thus to improve decisionmaking." The breadth, depth, and type of analysis depend on the nature, scale, and potential environmental impact of the proposed project. An EA "evaluates a project's potential environmental risks and impacts in its area of influence, a term defined as the area likely to be affected by the project, including all its ancillary aspects." EAs are to take into account the natural environment, human health and safety, social aspects, and transboundary and global environmental aspects, and to consider natural and social aspects in an integrated way. Depending on the scale of the impacts, the Bank may require an Environmental Management Plan, which "details the measures to be taken during the implementation and operation of a project to eliminate or offset adverse environmental impacts or reduce them to acceptable levels; and the actions needed to implement these measures."

Natural Habitats. This policy defines "natural habitats" as "land and water areas where (i) the ecosystems' biological communities are formed by native plant and animal species, and (ii) human activity has not essentially modified the area's primary ecological functions," and determines that "the Bank does not support projects involving the significant conversion of natural habitats unless there are no feasible alternatives for the project and its siting, and comprehensive analysis demonstrates that overall benefits from the project outweigh the environmental costs."

Certain natural habitats are defined as being "critical" if they are "(i) existing protected areas and areas officially proposed by government as protected areas, areas initially recognized as protected by traditional local communities and sites that maintain conditions vital for the viability of these protected areas or (ii) sites identified on supplemental lists prepared by the Bank or an authoritative source determined by the regional environment divisions." In this regard, "the Bank does not support projects that, in the Bank's opinion, involve the significant conversion or degradation of critical natural habitats." The term "significant degradation" is defined as "the elimination or severe diminution of the integrity of a critical or other natural habitat caused by a major, long-term change in land or water use," and the policy states, "Wherever feasible, Bank financed projects are sited on lands already converted (excluding any lands that in the Bank's opinion were converted in anticipation of the projects)." It appears that the impacts of quarrying of limestone have not yet been set beside OP4.04, and as the "supplemental lists" are developed, some limestone areas may be included.

Cultural Property. This draft Operational Policy states that the "Bank assists in protecting and enhancing cultural property encountered in Bank-financed projects, rather than leaving that protection to chance." The term "cultural property" refers to sites, structures, objects, and cultural landscapes (for example, parks, agricultural landscapes, and historic districts) "that have archaeological, paleontological, historical, architectural, religious, or other cultural significance." Such sites may be aboveground, underground, or underwater. "The Bank normally does not finance projects that will significantly damage cultural property, and it assists only those projects that are sited or designed so as to avoid, minimize, or mitigate adverse impacts on cultural property." The current Operational Policy Note (OPN 11.03) includes "sites with unique natural values" with or without cultural value. There is discussion as to whether to include this aspect.

2

Karst: Processes and Landforms

The Process of Karst Formation

There are large tracts of land in East Asia with spectacular topography: pitted plateaus, deeply dissected by closed despressions and with gorges in one or more directions; ranges of hills with jagged, razor-sharp crests; and towering hills rising from otherwise flat river plains or from the sea. These are limestone formations—sedimentary rocks that were built up millions of years ago by corals, shells, algae, and other marine organisms. Tectonic movements lifted them above sea level, often after a long burial beneath layers of sediment. Erosion first removed the sediment cover and then sculpted the limestone spectacularly into what are called "karst landscapes." East Asia has the world's largest single expanse of limestone (in China) and the largest tropical limestone caverns (in Sarawak, Malaysia).

Limestone dissolves in water at a rate that results in distinct landforms. The rate at which other kinds of rock dissolve in water is usually either too rapid to form karst landscapes or too slow, in which case chemical and mechanical weathering processes under the combined effects of sun, rain, and frost prevail. Rock types other than limestone, such as sandstone, gypsum, quartzite, and granodiorite, may sometimes develop karst-like features, but only under special climatic or geomorphic conditions.

Following weathering, the rock is removed by mechanical and chemical agents of erosion. In most areas, these processes work mainly on the surface of the rock, and most of the rainwater drains off aboveground in an orderly pattern of streams and rivers. However, water as a dissolving agent affects limestone bodies as a whole. Particularly in the tropics, small pores in the limestone surface can be effectively sealed off by the residue left by evaporating rainwater that first has dissolved small quantities of limestone. This increases the resistance of the surface rock to further erosion, a process called "case-hardening." Joints and larger cracks, usually abundantly present in limestone rock, take in increasing amounts of rainwater and enlarge in the process as the surfaces are dissolved. Often, no water at all is drained off superficially, and the absence of an aboveground drainage pattern is characteristic of karst areas. Although the external surface of the rock body dries quickly after a shower, the water inside may circulate for a long time through voids dissolved in the rock. Internally, a body of limestone is therefore often full of caverns and passages, while from the outside it still stands as a hill.

The solubility of limestone (consisting primarily of a mineral called calcite) is low in pure water, but increases with the concentration of acids. Humic acid from leaf litter; sulphuric acid from hydrothermal activity, bacterial processes, or sulphide minerals often present in the rock; and carbon dioxide are the most important agents (as well as, more recently, acid rain). Pure rainwater acquires aggressive dissolving properties when seeping through soil covering a limestone body. At this time the carbon dioxide concentration may become 100 times higher than in the atmosphere. Acids, released by either the soil or by minerals in the rock, further increase rainwater's dissolving capacity. This water is, in the long run, capable of eroding limestone rock surfaces beneath a soil cover and widening cracks into caves and gorges. It will also line cave walls with stalactites, stalagmites, and other features together called speleothems, because once it emerges from a tight fissure into the air, some carbon dioxide will escape from the water, so that it suddenly becomes "supersaturated" and precipitates calcite. Soil, and the vegetation cover protecting the soil, are therefore crucial to karst development; their removal leads to major disturbances in the karst process.

In some cases, erosion by sulphuric acid (from the sources mentioned above) is predominant. It can result in particularly large caves and spectacular speleothems formed from gypsum (calcium sulphate): huge chandeliers, gypsum needles more than a meter long, flexible gypsum "hair" draping over rockfalls, or gypsum "flowers" up to 1 kilogram in weight.

Finally, the dissolving action of water will undercut a limestone body, internally in caves and externally by rivers. Little by little, the hill collapses, which often results in extensive talus slopes at the foot of steep cliffs.

Aboveground Karst Landforms

There are various classifications of karst landscapes. Today, only a few types are regarded as having some relevance. These types, doline karst, cone karst, mogote karst, and tower karst refer to the different land forms resulting from different intensities or periods of weathering. Doline karst has rounded depressions, and tower karst has sheer cliffs, sometimes undercut.

To understand karst formation requires seeing it as a system. The features of a karst landscape depend on the interaction between the components of this system: water, air, soil, rock, life, energy, and time. The integrity of karst systems depends on the preservation of this interaction. A slow change in a few components may cause the formation of new karst landforms over the old ones. If the balance is upset by sudden changes in one or more components, the whole system may be disrupted.

The Lure of Unexplored Territory: Caves in the Thungyai Naresuan Wildlife Sanctuary, Western Thailand.

The topographic maps of western Thailand reveal a large expanse of karst landscape with numerous sinking streams and dolines that, until recently, had escaped all attention. A proposal to survey the caves in this area met with the enthusiastic approval of the Thailand Research Fund, a quasi-NGO sponsoring research in Thailand using Thai government money. To date, the fund has donated 2.5 million baht for the project. The project's objectives are to locate, explore, and map the caves in the area, with special regard for environment, geology, geomorphology, biology, archaeology, cultural aspects, hydrology, and palaeontology. A database containing all the information collected will be assembled, and maps of the surveyed caves will be included. After completion of the project, the database will be expanded to cover the whole of Thailand. The stored information will be used to improve cave and karst management in the country, and to increase public awareness of caves and their interest.

Figure 1. Aerial view of the 320,000-hectare Thungyai Naresuan Wildlife Sanctuary, much of which remains unexplored. (photo by Dean Smart)

Climatic conditions, rock properties, the geological environment of a karst area, and its tectonic setting determine the type of karst landscape that will develop on a given site:

- Climate: The most spectacular karst landscapes develop in areas with a high rainfall. In some arid areas, distinctive karst features may be almost entirely absent. One important factor in the humid tropical karst areas of East Asia is that the climate has been broadly the same for may millions of years, allowing time for complex suites of karst landforms, including very large caves, to develop. In contrast, many temperate areas have had cycles of warm and cool climates over the past 1 to 2 million years. During the cool phases, the rate of karstification is reduced and earlier landforms may be destroyed by ice or buried by sediments.

- Geological environment: The nature of the rock surrounding the limestone outcrop influences the development of karst features. For example, a limestone outcrop surrounded by mechanically weaker sediments is more vulnerable to erosion than an outcrop walled-in by large bodies of extremely resistant rock. Another example is the presence of alluvial sediments overlying the limestone bedrock. Quantities of soil and of insoluble residue originating from dissolved limestone also influence the shape of the karst. They increase the dissolving capacity of percolating water and may act as an abrasive. Large quantities of other sediments in karst landscapes often gather, forming plains over limestone bedrock that increase in size by erosive undercutting of the bordering hills.

- Tectonic setting: Tectonic uplift may lower the basal drainage level of a landscape and initiate the formation of karst features in limestone outcrops.

- Structure and properties of the limestone rock: Its mechanical strength, chemical purity, and porosity influence the shape of the developing karst. In soft, pure limestone, or in impure limestone (such as sandy limestone), mechanical erosion may exceed erosion by solution, and few karst features may form. In porous limestone, the surface layer of the rock may be cemented to a hard cap that covers a hill and protects the soft rock underneath. Of particular importance is the nature and spacing of joints and bedding planes in the limestone body.

Karst develops into a great variety of forms, but the classical karst cycle prevailing in many East Asian countries can evolve only in a region that has:

- Very thick limestone sequences: If the limestone is not sufficiently thick, the entire sequence is eroded away to expose the underlying rock before the karst has properly developed.

- Required climatic conditions: Long periods of warm and wet climates ensure that the dissolution process can be maximally effective.

- Slow and overall tectonic uplift (more or less matching the lowering of the base level of the landscape by dissolution): This is the only way in which a landscape with high karst towers can develop.

In most karst landscapes, features caused by different climatic conditions in the geological past are present, partly overprinted by more recent features. In dry and hot regions, or in temperate regions, for example, huge karst towers may stand as fossil landforms formed under much more humid climates in the past. This makes karst landscapes important archives, in which unique information about the past is stored.

On limestone surfaces above or beneath soil cover, dissolution also results in a range of shapes; ridges and peaks with sharp edges, deep furrows in steep rock faces, and patterns of polygonal depressions (dolines / sinkholes) in horizontal rock surfaces. These shapes—large and small—often create an extremely inhospitable landscape. Karst landscapes may be so inaccessible that they often stand as the last remnants of natural environment in densely populated agricultural land or even towns.

Dolomitic Limestones

Dolomite is limestone in which part of the calcium has been replaced by magnesium. Karst landscapes can develop on dolomitic limestones, but the landforms are usually somewhat different in shape. Generally, the karst relief in dolomitic limestones is much more subdued than in high-calcium limestones, and caves are less common as the dolomite weathers to produce a less soluble "sand."

Caves

Caves are generally the best-known karst feature; their presence is often known by the local inhabitants, and they occur most commonly in limestone rock. They are formed along lines of weakness in limestone rock. Usually, limestone rock bodies are jointed in two or three different directions, often more or less perpendicular to each other. Along lines where joints of different sets meet, and particularly at the top of the underground water table, cave passages may be formed by a process called "mixture corrosion." Percolating rainwater and groundwater, both saturated with dissolved limestone but at different carbon dioxide concentrations, mix into a fluid that is undersaturated with limestone (at that particular carbon dioxide concentration) and are thus able to dissolve considerable quantities of limestone again. As long as a cave passage is entirely filled with water, erosion takes place on the entire surface of the cave, often leading to typical polygonal depressions and "scallops" in the cave wall. Once air enters, the shape of the cave usually changes, and the growth of speleothems—often wonderfully shaped deposits formed by the precipitation of calcite—may start. Familiar examples are stalagmites and stalactites, but many other types exist. Water dripping onto the cave floor may form rings similar to the shapes formed momentarily when a raindrop falls into a puddle; small spheres known as "cave pearls" may form where drops of water fall on dry sediments and calcite is deposited on the grains. Calcite may precipitate out of water as it flows over cave walls and floors, forming intricate patterns of cascade basins, "curtains," and "frozen waterfalls," often of beautiful colors because of impurities in the rock. On cave floors covered with shallow water, coral-like spikes, fans, and glistening crystals may grow. Speleothems often convert caves into landscapes of immense beauty, reducing even a noisy group of tourists to a meek, whispering herd.

Once a cave passage is abandoned by the underground water, usually because of a lowering of the water table or an uplift of the area, newly formed cave systems lower in the rock body take over, and the dry cave is called a relict cave. Often, a number of generations of caves occur, with the oldest caves topmost in the limestone hill and the most recent ones slightly below the present level of the land surrounding the hill. The morphology of a relict cave, the pockets of sediment occurring in concave parts of its floor, the fossils present in those sediments, and the speleothems often contain information about the geological, biological, archaeological, and climatological past of the area. This makes karst landscapes important archives of unique information about the past.

3

Life in Karst Regions

Life Aboveground

Soils developed from limestone bedrock, if present at all, are often thin and deficient in most nutrients except calcium and magnesium. These two elements are often present in excess, and tend to restrict the availability of important nutrients to plants. It is quite common for limestone to be covered by sediments brought from outside the area by rivers or wind. Soils developed on the sediments are quite difference from the limestone soils. Because of the predominantly underground drainage of karst areas through cracks in the rock, organisms living on limestone are also subjected to periodic and prolonged drought. The thin and often patchy vegetation cover may also provide little shade. In general, the environment in a karst area is much harsher than in surrounding areas on other bedrock, although collapse dolines, deep gorges. and crevices may provide protected, well-shaded, and damp habitats locally. In depressions in rocky plateaus without drainage, leaf litter and other organic matter sometimes gather in puddles of still water, particularly in areas with a perpetually wet climate. In Irian Jaya, Indonesia, these have developed into extensive rain-fed bogs.

Life in Caves

Lack of light is the most determining factor for all life in caves, small voids, deep cracks in the rock, and open spaces in talus fields. According to the degree of darkness and other physical conditions, the cave environment can be divided into four zones, starting at the entrance:

- the twilight zone near the cave entrance, where light intensity, humidity, and temperature vary and a large and varied fauna can be found

- the transition zone, of complete darkness but still variable humidity and temperature, where a number of common species live, some of which make sorties to the outside world

- the deep zone, of complete darkness and almost constant 100 percent humidity and constant temperature, which is the home of fully cave-adapted species that never venture outside the cave

- the stagnant zone of complete darkness and 100 percent humidity, where there is little air exchange and carbon dioxide concentrations may become high.

As a result of the high humidity in the deep zone, a condition that would drown many surface creatures, the differences between terrestrial and aquatic life tends to blur. For example, a cave fish species that creeps over wet rock, above the water level, is known. Plants cannot grow here, although roots may and often do penetrate the cave ceiling. The most important effects of this exclusion of green plants are to make all almost cave dwellers dependent on organic material brought in from the outside[2], and to exclude all animals that feed directly on the aboveground parts of green plants. In the deepest, most isolated parts of caves, the air may be stagnant, and carbon dioxide concentrations may be so high that, for humans, breathing is difficult. Here, too, organisms are adapted to cope with this environment.

Energy is available in localized deposits of organic material: piles of guano (dung) below the roosts of bats and swiftlets; organic material falling into the cave through crevices in the roof; drift material washed in by streams, particularly during floods; and material (insects, for instance) drawn in by drafts. Particularly in the tropics, tree roots are also an important source of organic material; many trees, such as figs, survive the harsh surface environment by sending roots deep into the rock, often down to the water table. Specialized organisms, including microorganisms such as fungi, protozoa, and mineral-fixing bacteria, use these deposits, and a food chain of giant arthropods, such as crickets and centipedes, dissipates small amounts of organic material throughout the cave system, down to the deepest recesses.

Because of the absence of light, many true cave animals do not display any daily or seasonal rhythm in their activities. Some, however, have a daily rhythm imposed upon them, for example, by the daily rhythm of drafts, but in particular by the departure and subsequent return of bats and swiftlets. In their absence, food is not available for the free-living parasites in the roosts, and there is a halt to the rain of fresh feces on which the numerous inhabitants of the guano piles feed.

Life in the Dark

Caves are one of the most peculiar terrestrial ecosystems. They host communities of, in our eyes, strange species adapted to extreme conditions. Green plants, which form the matrix of nearly all aboveground ecosystems, are absent. To cope with the permanent darkness, extreme patchiness of food, and relatively constant climate of the underground voids, cave animals have all developed physiological, behavioral, and morphological adaptations. They lose many of the essential functions of aboveground species: Their eyes are reduced or absent, and they have little or no pigment. In contrast, their ability to regulate water is enhanced: They have developed means of expelling water in 100 percent humidity and expelling excess water without losing body salts. If their ancestors had wings, cave animals have lost them. Diurnal rhythms are lost. Their life span increases, and their fertility decreases dramatically. These adaptations have confined cave species to their habitat—they cannot survive elsewhere. If the cave in which they live is destroyed, they perish.

East Asian cave fauna include many exceptional organisms. A few examples are given below.

- Cave fish: Cave fish are fragile white or pinkish animals, with reduced eyes, devoid of scales and pigment. They are present in small populations in some caves of Thailand and China, and most species are restricted to only one or two caves. They often occupy niches that outside fish, which frequently enter caves, do not reach. In the Lao PDR, a new genus of cave fish was encountered at the bottom of a 20-meter-deep cave passage.
- Giant insects: Among the most spectacular species are the giant crickets, centipedes, spiders, and whip-scorpions that roam the cave walls of the region. They need both darkness and an adequate food supply, which is provided by surrounding guano piles.
- Aquatic woodlice: Most of the world's woodlice are terrestrial, but a truly aquatic species, *Thailandoniscus annae*, is found in Phangnga bay, southern Thailand. This remarkable animal is known from only one population, which lives in a small pool in Tapan cave, and has never been found in any other cave in the region, nor in any other pool in the same cave.

The insulating role of the walls and roofs of caves effectively buffers the relatively wide, daily variations in temperature and humidity of the outside world. Day-to-day conditions thus remain fairly stable, especially deep within a cave, but there are still seasonal changes that can more or less alter the conditions in the cave. For example, during the rainy season the humidity and amount of free water within a cave tend to increase. Air movement is also buffered by the cave walls, but still occurs as air is drawn out of the cave during the day, when the air outside is warmer and lighter. This air movement follows a regular pattern, but leaves pockets of still air in deep caves, where spiders can weave delicate and complex webs, and preserves pockets of high humidity. In these deeper areas, the concentration of carbon dioxide increases if there is no inflow of air except from the cave mouth.

It is likely that life in underground communities will turn out to be richer and more diverse than scientists could ever have anticipated. Many species that are found in caves live, in fact, in small voids with a relatively high humidity and high levels of carbon dioxide, and only occasionally wander off into larger caves where they may be seen by people. Most limestone bodies are riddled with such small voids, even when larger caves are not present.

Endemism

A species is endemic if its range is restricted to a specific geographical area. Endemic species are regarded as particularly precious elements of the earth's biodiversity. Depending on the context, the term "geographical area" may refer, for example, to a *site* (for example, a mountain top) or to a *biogeographical region* (for example, the island of New Guinea and surrounding archipelagos).

In connection with endemism, certain terminology is used in this report. These terms do not represent sharply delimited classes of species, but rather extremes, or marking points, in a continuous spectrum of possibilities. The first set of terms addresses evolutionary isolation:

- A *recent endemic* species belongs to a cluster of closely related species that have evolved from a single parental species in the recent geological history.

- An *ancient endemic* species is a last surviving or relict species of often large groups in the distant geological past. Often, no evolutionary relatives are extant, and the species is the sole living representative of a high-ranking taxonomic group.

The second set of terms addresses the size of the area to which a species is endemic. The circumscription of these terms has been adapted to suit the geographical properties of limestone habitats, and the purposes of this report:

- A *site-endemic* species can have a range of up to about 100 square kilometers, but sometimes has a range down to much less than 1 square kilometer (for example, a snail species with a range of about 200 square meters, or even a fish species with a range of 6 square meters). Typically, the range covers a single limestone hill, or a group of karst hills on the same body of limestone bedrock.

- A *local-endemic* species has a range of about 100 to 10,000 square kilometers. The range typically covers two or more geologically separated bodies of limestone bedrock, which are often embedded in larger topographical units, such as a mountain chain.

- A *regional-endemic* species has a range covering 10,000 to 1 million square kilometers (for example, the island of Borneo).

- A *widespread species* has a range larger than 1 million square kilometers.

In addition, the term *island endemic* is often used, but only to denote that the species range is confined to an island; it may belong to any of the first three size classes.

Many limestone endemics, although occupying a sizable range, occur on only a few limestone outcrops that together cover only a minute fraction of that range. These species occupy a very small area ; they are "rare" species. Limestone outcrops in cleared land, and particularly the narrow fringes of original vegetation surrounding them, may support the last remnants of communities that previously occupied large parts of the area, both on limestone as well as on other rock types. Although they are not limestone inhabitants in the strict sense, the range of the species living there may have been so much reduced that they are as vulnerable to extinction as true limestone species. The occurrence and threatened status of such species should be considered when assessing limestone communities.

Biodiversity Assessments

The 1982 United Nations World Charter for Nature and the Preamble to the 1992 UN Convention on Biological Diversity make it clear that, ideally, as much biodiversity as possible should be conserved because of its intrinsic value, not primarily for its economic value. The growth of tourism to wild areas clearly demonstrates that people's mental and spiritual health are improved by contact with nature.

Thus, while global biodiversity is valued as an economic resource, it is also as a part of the human inheritance—something that needs to be preserved for the well-being, in the widest sense, of present and future generations. We realize that we cannot survive without biodiversity. Although life in general has survived more cataclysmic events in the geological past than anything humankind can devise at present, we remain uncertain about the quality of the life that might be in store after the earth's biodiversity has been disrupted.

The imperative for conservation often opposes certain economic development activities, and, in most cases, these impose difficult decisions about resource use. Biodiversity assessments for which consultants need to attach a value to single species as well as areas, help to make these choices. Because it is difficult to attach numerical values to biodiversity, nonquantified relative biodiversity values are often used on an ad hoc basis. To do so, the following factors are among the more commonly considered:

- Evolutionary (phylogenetic) isolation of a species: More value is attached to ancient endemics than to recent endemics. For example, the discovery of a primitive fish off Sulawesi, belonging to a group thought to have been extinct for hundreds of millions of years, causes more scientific and popular excitement than the discovery in Papua New Guinea of an orchid that belongs to a group containing more than 400 species locally.

- Uniqueness of a species: More value is attached to a species showing unusual features or adaptations to habitats in which its relatives cannot survive, such as caves.

- The role of a species in supporting the ecological system in which it occurs (keystone species): The extinction of the sole pollinator of a dominating plant species in an ecosystem may lead to the collapse of the entire ecosystem; the extinction of a snail feeding on algae may impoverish the ecosystem but will not destroy it.

- Uniqueness of functional groups: Certain species may use similar parts of the natural resource or may exhibit common behavioral adaptations to the environment. Rather like the situation with keystone species, the removal of one or more of these groups may have a dramatic effect on the stability of the ecosystem.

- The range size of the species occurring within an area: The destruction of natural habitat within an area is likely to be a mortal blow to a site-endemic species, and of little consequence for the survival of widespread species. The area of occupation is also important here: even a widespread species occurring on only a small number of widely scattered sites within its range could be brought to extinction if, for instance, the sites were all isolated limestone outcrops sought by quarrying companies.

Unlike other elements of environmental assessment, such as water quality or noise, biodiversity assessments are not yet subject to standards or norms. Techniques and understanding are developing so that standard protocols will evolve, but for the time being it is necessary to work on a case-by-case basis, sharing information and conclusions to build up the knowledge of biodiversity richness, functions, uses, vulnerability, and threats.

Estimates of the number of animal and plant species worldwide vary widely, and run from some 5 to 15 million. So far, only very basic information is available for about 1.75 million of these. Understandably, some groups have received more attention than others: almost all the bird species have been named by now, but only about 10 percent of the insects. Similarly, our taxonomic knowledge of the European and North American biodiversity is more complete than that of any tropical region in the world.

Tropical limestone areas are, in a biological sense, among the least studied in the world. Local biodiversity assessments have to be based on incomplete information. Biodiversity consultants will use arguments that usually concern the occurrence of species and species categories (or communities rather than individual species). The most frequently used categories are:

- Umbrella and flagship species: Protection of an area is advised because of the occurrence of a single species. This may be a species with such wide ecological requirements and geographical range that one can expect that numerous other species will enjoy protection in its wake (umbrella species), or a species sufficiently popular with people to serve as a symbol (flagship species). Many areas are protected as a result of such arguments. They do not necessarily imply a high biodiversity value, nor a high species richness.

- Species with direct economic value: This category includes, for example, bat populations, which are crucial for the pollination of crops and the reduction of pests, or plant species with potentially medicinal properties. Again, this is a selling argument and does not imply high biodiversity value or species richness.

- Species of exceptional biodiversity value, or rare or threatened species: The occurrence of such species does, of course, imply a high biodiversity value, but not necessarily a high species richness. Sometimes, these are also flagship species, such as the tiger.

- Reference or indicator groups: Applying this criterion involves extrapolating a general biodiversity value from the local representation of a single group, under the assumption that an area containing species of one group will also contain species of another. Depending on sampling efficiency, the assumption may or may not be justified, but a careful application may indicate both a high biodiversity value as well as high species richness.

- Complete species lists of all biota (or at least of a number of key groups): This goal is rarely achieved, but if additional information on these species is used to advantage, it can offer some of the best arguments for protective measures.

Many proposed methods for biodiversity valuation are of limited value because they assume near-perfect taxonomic and evolutionary knowledge. Meanwhile, specialists are hard-pressed to find ways around the problem of insufficient taxonomic knowledge, and in some instances their methods do have a predictive value. Quite often, however, biodiversity consultants will have to work with reference groups, attaching ad hoc biodiversity values to species and communities based on their specific and deep knowledge of the groups studied. Many species have restricted geographical ranges, so it is difficult to establish a method of uniform comparison between geographically remote areas where, for example, the species differ but the physical environment and functional groups are similar. Recent studies indicate that combining information about plant species and functional groups can greatly improve predictive capacity and make possible meaningful comparisons about biodiversity among different countries. Another problem is posed by considering richness as a primary criterion for assessing biodiversity value; for example, there are many sites where species numbers are low but uniqueness is high.

The Red List Problem

Red Lists and national lists of protected species comprise species that are nationally or internationally recognized as vulnerable, endangered, or presumed extinct. They are supposed to serve as a reference but, however useful for some purposes, they should be used with great care. These lists are in most cases only more or less complete for some groups of higher vertebrates. Any taxonomist working on less conspicuous groups of organisms or any group of invertebrates can attest to the overall incompleteness of the lists. Each limestone biodiversity specialist could add to it tens, or even hundreds, of species from the groups of organisms they have studied.

A mistaken interpretation of Red List species is that, if no listed species is recorded on a site, the site cannot be a candidate for conservation. Many limestone caves and other environments, which often host extremely valuable components of the earth's biodiversity, may thus be legally overlooked in conservation and other development programs.

Endemism and Karst Landscapes

Karst areas under humid tropical conditions are home to numerous plant and animal species with an extraordinarily small range.[3] This is thought to have originated in the extreme and diverse environmental conditions on tropical karst surfaces, such as:

- Deleterious effects of a high concentration of calcium and magnesium in the environment.
- The marked topography of many karst areas (steep-sided hills, dolines, plateaus, and caves) and a large altitudinal range in combination with the often intricate pattern of acid and alkaline soils.
- Extreme dissection of the karst surface: Particularly in tower karst, numerous limestone hills are separated by valleys with a noncalcareous, alluvial topsoil. For limestone-dependent plants and animals, such hills are as isolated from one another as are islands in a sea.
- Extreme climatic conditions, such as exposure to the sun, torrential rain, and drought due to very efficient, mainly underground, drainage systems.

The Smallest, Hottest Hotspot of Cave Biodiversity in East Asia
More than 400 caves have been surveyed for their fauna in East Asia, from Sulawesi to China. The freshwater arthropod fauna of each of these caves usually consists of only one to four endemic species. The underground system of two small caves (Tham Phulu and Tham Kubio) in eastern Thailand, is an exception. These caves are used as a sanctuary by Buddhist monks and have two small pools each, in which six highly specialized cave species live, all in large numbers. All these species but one are so far restricted to these caves. Two of the species are the only representatives of a genus, and therefore of high biodiversity value.

These conditions exert a strong ecological pressure on any species not adapted to them. The species may respond in two ways to the pressure: local extinction, or adaptation by accelerated evolution (often after a reduction of the number of individuals). In the process, isolated populations in this highly fragmented environment are likely to develop into distinct species. Some adapt so thoroughly that the land surrounding the karst area, possibly still inhabited by their evolutionary predecessors, has become uninhabitable territory for them. Such limestone-restricted species can no longer shift to nonlimestone habitats.

4

Some Major Groups of Karst Organisms

Many species of animal and plant groups are represented in karst landscapes, and a relatively large proportion is endemic to small areas. These may consist of small, inconspicuous species, and even include species regarded as unpleasant by some (for example, large spiders). Some arthropods (insects, spiders, crabs, shrimps, centipedes, millipedes, and related organisms with jointed external skeletons) have added significance not only because of the sheer number of species they include, but also because they are a fundamental part of many food chains. Their importance, and that of many other groups of small species, is increasingly recognized. The animal and plant groups below serve only as examples of limestone biodiversity; other groups may be equally interesting and important.

Arthropods: The Bulk of Biodiversity

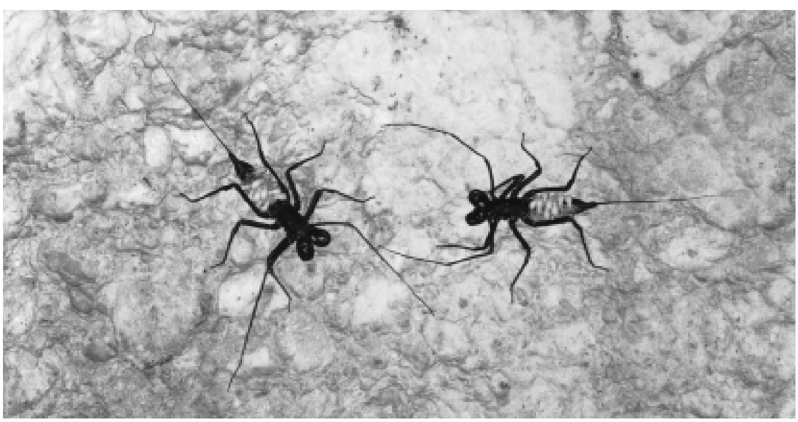
Arthropods are by far the most diverse among the numerous groups of organisms, and they live in virtually all terrestrial and aquatic ecosystems. Preserving arthropod diversity clearly is preserving the core of biodiversity. Their environmental importance is inestimable: arthropods have an essential function in all major biological processes.

The available data suggest that arthropods represent more than 60 percent of all living organisms in the aboveground habitats of East Asia, and each year numerous new species are discovered. In underground habitats, where green plants are absent, this proportion probably reaches more than 90 percent. Each biological sample collected in an area not previously studied appears to result in 50 to 90 percent of the collected species being new to science. The basic work of biological inventory is far from complete, but all evidence points to a high arthropod diversity.

It is uncertain whether limestone areas host more arthropod species, or a more diverse arthropod fauna, than areas on other types of bedrock. The data are not conclusive, but limestone areas, more than areas on other bedrock types, are very often reservoirs of biodiversity, encircled by land with a very low biodiversity value that is under permanent human influence.

The total number of species for each karst area is likely to be rather similar throughout East Asia. However, the composition of the fauna differs greatly from region to region. Each hosts fauna with unique properties, such as species composition, number of endemics, and vulnerability of individual species as well as species communities. On a smaller scale, this pattern is partially repeated: some, but not all, individual karst hills have fauna with unique elements. Particularly in extensive karst areas, the disturbance of a single site within the area may have little impact on the arthropod biodiversity of the area as a whole. An exception to this rule involves guano communities, which may occur very locally—for example, restricted to the guano piles of a few bat or swiftlet colonies.

Figure 2. Long-Tailed Whip-Scorpions as Caring Mothers



Giant, long-tailed whip-scorpions (measuring up to 10 centimeters without the tail) have recently been found to be regular inhabitants of the huge cave systems of southern Lao PDR. Small groups of females bearing their eggs and young on their backs are found in the deep parts of the caves, resting motionless for days on the walls if left undisturbed. How and why these concentrations of large, non-cave-adapted arachnids form in such remote and unfavorable environments remains unknown. (photo by J. Lordon)

Arthropods and endemism. The arthropod fauna of the limestone areas of East Asia include a very high proportion of site-endemic and local-endemic species. All karst areas sampled so far have yielded a number of such species. The little evidence available indicates that tropical cave arthropods tend to have smaller ranges than cave arthropods in temperate climates.

Patterns of arthropod biodiversity. In relation to arthropods, three major ecosystems can be distinguished in limestone areas. Each hosts a distinct arthropod assemblage and is vulnerable to disturbance in its own characteristic way. Each ecosystem includes both land and freshwater habitats.

- The aboveground ecosystem: The majority of the arthropod species in limestone areas lives aboveground, in the primary and secondary forests that cover most of the limestone areas of East Asia. Most species live on the vegetation, in leaf litter, or in soil. They are often host specific and restricted to the range of their plant or animal host. Their range is not usually restricted to limestone areas. Nonetheless, there are also species restricted to habitats on or near outcropping limestone rocks.

- The underground ecosystem: Arthropods are represented by a much smaller number of species in caves and underground voids. These, however, have a high biodiversity value because of the prevalence of highly specialized endemics. The underground environment can be divided in two ecosystems, mainly characterized by the availability of energy:

  1. The low-energy ecosystem: In the deepest recesses of caves and small voids, food is scarce. The fauna consist of small numbers of scattered individuals. Arthropods are by far the dominant animals. Extreme conditions have led to the development of often spectacular adaptations: very long life cycles, reduction of eyes and wings, white coloring through loss of pigment, and long antennae to keep in touch with the surroundings in pitch darkness. Because of this, and because most species are endemic to only a small area, their value as unique functional groups largely surpasses that of mere species number.

  2. The high-energy ecosystem: Guano piles produced by bats and swiftlets feed huge, localized populations of narrowly

specialized, unique organisms that include species of crickets, cockroaches, millipedes, beetles, moths, flies, and springtails. They are preyed upon by the impressive giant carnivorous arthropods of tropical caves, such as tailless and long-tailed whip-scorpions, giant long-leg and short-leg centipedes, giant spiders, and a number of poorly known mites and other small predators. Adaptations of species specializing on guano deposits are the opposite of those of the low-energy ecosystem: life cycles are short, and eyes, wings, and pigment are usually not reduced. This implies a somewhat higher environmental mobility in these animals, which may explain the lower proportion of site-endemic species.

Land and Freshwater Molluscs

Land and freshwater molluscs (snails and clams) contribute to the biodiversity of karst areas because of the large numbers of species and individuals, and because of the occurrence of site and local endemism. All shell-bearing species need calcium carbonate (limestone) to build their shells, but their dependence on the vicinity of a limestone outcrop varies greatly. For some species, the presence of outcropping limestone seems vital, whereas others have developed the means to obtain shell construction materials elsewhere.

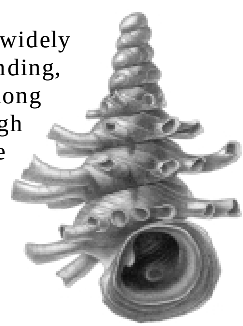
The ecological importance of molluscs is considerable: for example, snails, which can be herbivores, omnivores, or carnivores, are preyed upon by a large number of other animals, ranging from insects to birds to mammals. Our knowledge of the life cycle and behavior of the East Asian species is largely restricted to some salient features not commonly associated with these animals: a Malaysian species, for instance, with a luminescent body; various other species that are able to creep with (for a snail) extraordinary speed, or to wriggle violently or even jump when threatened. A Philippine species emits a high-pitched sound when picked up! Carnivorous species may be found pursuing an earthworm or attacking other, much larger snails. Some western Indonesian species that live on the foliage of trees construct nests hanging from a branch by folding together two leaves; some species in the western Pacific carry their eggs in the hollow lower surface of the shell. Another group of species in the Pacific lays one egg at a time and bestows great parental care on the young.

Beautiful Snails from the Limestone of Borneo

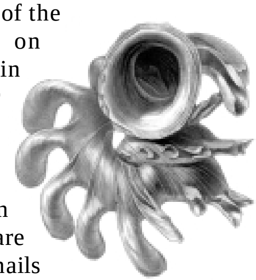
Land snails of the family Diplommatinidae are often spectacularly shaped and would be highly prized collectors items if only they were larger than their 1 to 8 millimeters in height. Hundreds of species occur throughout Southeast Asia, living an inconspicuous life on vegetation, in leaf litter, or on rock outcrops. Feeding on minute algae, they are harmless enough (species of some other families, with equally small shells, are ravenously carnivorous). These snails have a very short life cycle: they develop into adults within a few months after hatching (the shell growing at a rate of one rib a day), then they mate, lay their eggs, and die, all within a year. Most species have taken on camouflage coloring or are almost invisible because they glue soil particles between the ribs of their shells. Some, however, have projecting ribs and are extremely conspicuous. In the morning sun, they stand out against dark rock as minute, brilliantly white fans, or tufts of pure white cotton wool, often covered with glistening droplets of dew. It is tempting to speculate that these mimic a species of aphid living in the same environments, which has its body covered in sticky, white scales, and thus proclaims its foul taste to potential predators.

Recent research has shown that Borneo is inhabited by at least 150 species of this family. About 100 of these were found to be new to science. Many more new species can be expected once the limestone hills in Borneo's deep interior are surveyed. The numerous species that live only on moss- and algae-covered limestone surfaces are often restricted to one or a few small limestone hills. Although some are comparatively safe, others are much less so, and some are already extinct because of habitat destruction.

- *Diplommatina miraculumdei* occurs in numerous, widely scattered populations on the limestone hills surrounding, like a necklace, the crest of the 200-kilometer-long Meratus Mountains in southeastern Borneo. Although the limestone environments are threatened by the combined effects of shifting cultivation, wildfire, logging, and mining, the species is under no immediate threat of extinction. Many populations may be wiped out, but some will survive.



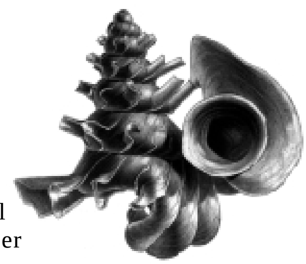
- *Opisthostoma grandispinosum* is an example of the more than 50 species that occur only on Gunung ("Mount") Subis (Batu Niah) in Sarawak, Malaysia, a 15 square kilometer limestone hill that is now a nature reserve. Although a part of the hill is quarried for cement, most of the area is maintained in a semipristine condition because it includes the Niah Caves, which are a major tourist attraction. The endemic snails are relatively safe.



(continued)

- *Opisthostoma lituus* is one of six snail species restricted to an isolated limestone hill (that is, distant from other limestone outcrops) of about 0.2 square kilometer ground surface. The hill may be threatened because the area has been opened up for various purposes. The species is vulnerable.

- *Opisthostoma mirabile* is restricted to two limestone hills in East Sabah, Malaysia. The smallest hill was destroyed to provide road metal. The snail still survives on the larger hill (Gunung Suanlamba), which is now protected because its caves (the Gomantong caves) host large colonies of swifts. The vegetation on the hill itself, however, is depleted, and the snail faces an uncertain future, as do nine other snail species endemic to this hill.



- *Diplommatina calvula* is one of the nine species discussed above. Two shells were collected a century ago, but the specimens were mixed up with shells of another species and were in a museum without having been recognized as a distinct species. D. *calvula* has not been found since and is probably extinct.

(drawings by Jaap Vermeulen)

Numbers of mollusc species and individuals in limestone areas. It is estimated that some 8,000 species of land and freshwater molluscs occur in East Asia, and about half of these are found most frequently in limestone environments. The number of species entirely restricted to these environments is likely to exceed 2,000.

Nonlimestone environments almost invariably host fewer species than limestone environments under similar conditions. The snail fauna of a single, undisturbed karst hill in East Asia average 60 different species, and may reach more than 100 species. In a worldwide perspective, this is probably above average. A comparable site on young volcanic soil yields only 30 species on average, occasionally reaching 50 species. A site on any other rock type will rarely yield more than 20 species.

The number of individuals living on any limestone hill is also larger than elsewhere under similar external environments. A bucketful of soil, processed to remove pebbles, clay, and earth, from near a rock outcrop typically contains from 1,000 to 10,000 shells (empty shells and living animals together), whereas a similar amount of soil from forest on volcanic rock usually yields only from 10 to 100 shells, and one from forest on any other rock type only occasionally has more than 10 shells. This holds even when a correcting factor is applied for the fact that soil sampling is a less adequate collecting method in nonlimestone environments.

Endemism among molluscs. The unique conditions in limestone environments have caused the development of numerous mollusc species that are restricted to small areas, particularly in the tropics:

- Species endemic to a site occur frequently among karst molluscs. In Sarawak, a limestone hill of about 15 square kilometers is probably inhabited by more than 50 snail species that occur nowhere else in the world, and another, 0.2 square kilometer hill is inhabited by six such species. Elsewhere, the occurrence of site-endemic snails has been ascertained in Peninsular Malaysia (up to seven species endemic to a single hill), and they undoubtedly occur in other countries. The number of site-endemic species on a karst hill appears to increase with distance from other karst hills. In East Asia, no nonlimestone environments are known to harbor site-endemic snail species, with the possible exception of a few volcanic mountains.

- Local and regional endemism is also common; up to two-thirds of the species at a site may fall within these categories. In many cases, their actual area of occupation may be restricted to some tens of square kilometers—that is, a few widely scattered, small-sized karst hills.

In addition to the above categories, the fauna at a site consist of widespread species and species that are unintentionally spread by people.

Endemism among molluscs in relation to ecological and taxonomic groups. Within the limestone environment, land and freshwater molluscs can be roughly grouped according to their ecological niche. Some groups are notably more vulnerable to habitat destruction than others:

- Land snails living aboveground and entirely restricted to limestone environments: Generally, these live on mossy rock surfaces or in thin, calcareous soil covering limestone rock. Site endemism and local endemism seem to be the rule. Relatively few species are widespread.

- Land and freshwater cave snails: For a long time, only very few freshwater species were known to be adapted to living in caves. Recent surveys into cave systems in Thailand brought to light the first terrestrial snails that can be assumed to live in deep soil, small voids, and caves. They belong to various families. In 1998, a single cave in Vietnam yielded 17 cave species, 15 of which belong to a single family.[4] As a rule, true cave molluscs are site endemics or local endemics. Some optional cave dwellers occur in association with guano deposits in caves; these are generally widespread species. Occasionally, other aboveground species may venture quite deep into limestone caves or may fall into caves through clefts in the rock.

- Land snails living aboveground, on limestone as well as on other bedrock: This group includes large numbers of species living in thick soil and on vegetation. Many are widespread or endemic to a large region. A smaller proportion is locally endemic, and site endemics are rare within this group.

- Freshwater snails living aboveground and restricted to limestone environments: This group includes minute species occurring, often by the thousands, in small springs and associated streams. Recently, shells of various species new to science have been collected in Malaysia and Vietnam. They belong to a family that is well known in Europe and North America for the large number of site endemics and local endemics it includes.

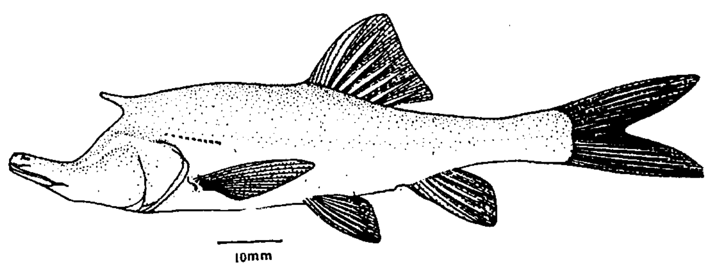
- Freshwater snails and clams living aboveground, on limestone as well as on other bedrock: These often occur in large numbers in rivers through and downstream of limestone areas. The distribution of many may be related to limestone, such as an unnamed clam species found only in collapse dolines above a subterranean river in southeastern Kalimantan; others may have survived habitat destruction elsewhere in the relatively clean waters of karst areas. Most species are widespread, but some families tend to site or local endemism. A dramatic example occurs is the Mekong drainage system, where narrowly endemic freshwater mollusc species occur by the hundreds.

Fishes in Limestone Areas

Fish species known exclusively from underground waters have developed morphological adaptations to this very peculiar habitat. The absence of light has made their eyes useless, and most species now have very reduced or nonfunctional eyes; many simply have no eyes.

Similarly, as a result of the absence of light, all cave fishes are more or less completely unpigmented, their bodies appearing pinkish-white. Several species are also devoid of scales. To compensate for the absence of eyes, several species have developed their other senses, and the lateral line (which fishes use to detect movements in the water) is more developed in some species. Others have elongated and slender paired fins, which they possibly use to touch the bottom and search for food. Several Chinese cave species of the genus *Sinocyclocheilus* have a marked head hump, which is supposed to have a hydrodynamic function and to help the fish keep their position in the very swift current (figure 3). Many species of this genus have also developed head protuberances of unknown function—one of them even looks like a unicorn. A cave loach from Thailand (*Cryptotora thamicola*) has been observed out of the water, using its large, laterally extended, paired fins to climb up moist cliffs and search for either food or suitable water bodies.

Figure 3. *Sinocyclocheilus hyalinus* from Yunnan, China. (from Chen et al. 1994)



Fish habitats in limestone areas can be divided into three main categories: underground waters, surface waters, and marine habitats. Only the first two are dealt with in table 1.

Fishes in underground waters. Numerous fish species from underground limestone environments are known, including species from caves and water-filled voids. The fish species range from surface species, which occasionally enter caves by accident, to those that are entirely adapted to the underground environment and never see daylight. Worldwide, some 70 species are known exclusively from underground environments. In East Asia, 26 species have been found so far (see table 1), but it is expected that the actual number of Asian cave fishes might

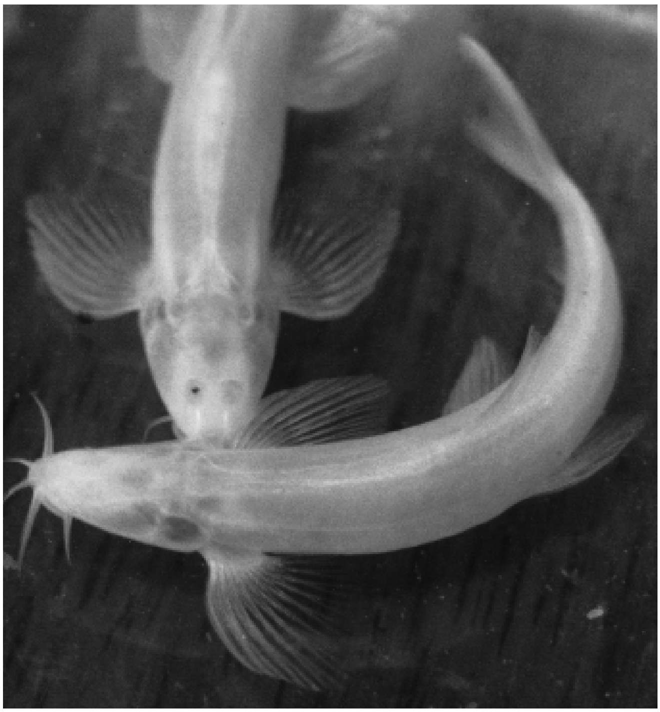
Table 1. Southeast and East Asian Fish Species Known Exclusively from Subterranean Waters

Species	*Location*
Family Cyprinidae	
**Poropuntius speleops*	Thailand
**Poropuntius* sp.	Thailand
**Puntius* aff. *binotatus*	Indonesia: Java
**Sinocyclocheilus anatirostris*	China: Guangxi
**Sinocyclocheilus angularis*	China: Guizhou
**Sinocyclocheilus anophthalmus*	China: Yunnan
**Sinocyclocheilus cyphotergous*	China: Guizhou
**Sinocyclocheilus hyalinus*	China: Yunnan
**Sinocyclocheilus microphthalmus*	China: Guangxi
**Typhlobarbus nudiventris*	China: Yunnan
**Troglocyclocheilus khammouanensis*	Lao PDR
Family Balitoridae	
*"*Cryptotora*" *thamicola*	Thailand
**Nemacheilus troglocataractus*	Thailand
**Oreonectes anophthalmus*	China: Guangxi
Schistura oedipus	Thailand
**Schistura jarutanini*	Thailand
**Schistura* sp.	Thailand: Phitsanulok
**Triplophysa gejiuensis*	China: Yunnan
**Triplophysa xiangxiensis*	China: Huanan
**Triplophysa yunannensis*	China: Yunnan
**Triplophysa shilinensis*	China: Yunnan
**Sundoreonectes tiomanensis*	Malaysia (Tioman Is.)
Family Cobitidae	
**Protocobitis typhlops*	China: Guangxi
Family Gobiidae	
**Bostrychus* sp. n.	Indonesia: Sulawesi
**Caecogobius cryptophthalmus*	Philippines: Samar
**Oxyeleotris caeca*	Papua New Guinea
Cave-adapted population of a surface species	
Pterocryptis buccata	Thailand

Note: Asterisks indicate species presently known from just a single cave.

be two or three times higher. All but three are currently known from a single cave. In addition, a cave-adapted population is known for at least one species that otherwise lives in surface waters. Most caves host a single cave fish species, a few host two, and in one cave, three different species have been found.

Figure 4. The cave loach (*Nemacheilus troglocataractus*) from Kanchanburi, Thailand. Note the upper fish has a rudimentary eye, the lower one has none. (photo by Richard Borowsky)



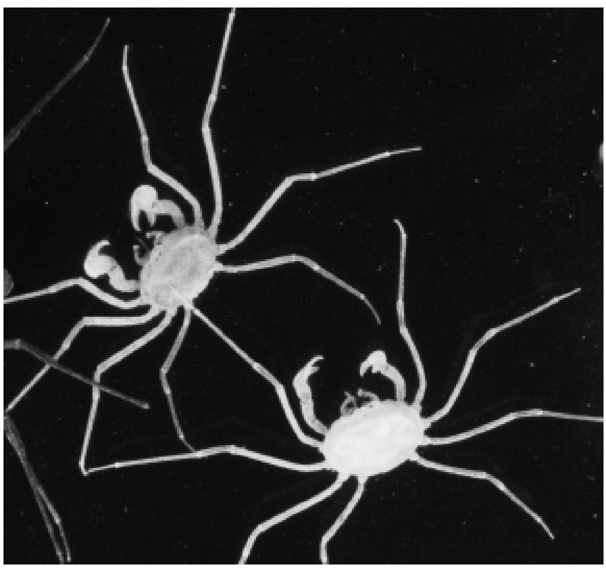
Fishes in surface waters. Fish communities from flowing surface waters in limestone areas are generally similar to fish communities elsewhere. Patterns of endemism follow the same rules, and any basin with an independent geomorphological history should be expected to harbor a few endemic species. Surface waters in limestone areas are characterized by poor development of a permanent network of water bodies, which are reduced to disconnected ponds and puddles during the dry season or dry out entirely. This creates a very harsh environment for fishes.

Several permanent lakes in limestone areas, or fringing them, are inhabited by unique fish communities with a large number of endemic species. Examples are Lake Inle in Myanmar (about 35 native species, including 9 endemic species and 3 endemic genera), as well as several lakes in Yunnan, China, such as Lake Dianchi (about 25 native species, including 12 endemic species and 1 endemic genus), Lake Fuxian (25 native species, including

12 endemics), Lake Erhai (16 native species, including at least 7 endemics), and several smaller lakes. Some of these endemic species have a very small area of occupation, as little as 6 square meters.

A distinctive and peculiar fish community also exists in some coastal rivers in limestone areas. Fish species normally occurring in estuaries or even in the sea have been found in pure fresh water beyond tidal influence in several limestone areas. The high mineral content of the water, caused by the dissolution of the limestone, results in an osmotic pressure close to that of sea water so that these marine species are able to live here.

Figure 5. Long-limbed cave crabs (*Cancrocaeca xenomorpha*) from the Maros karst, Sulawesi. (photo by Didier Rigal)



Swiftlets and Caves

Swiftlets are small birds of the swift family that, because of their short legs, can perch only on vertical surfaces, such as cave walls and cliffs. Swiftlets nest in colonies on perpendicular or overhanging cliffs and on the walls and ceilings of caves. Once a site has been chosen, it will serve as a permanent roosting place and nesting site, season after season, year after year. The only migratory swiftlets are the Himalayan representatives of Hume's swiftlet, which range south to the Andaman Islands, Sumatra, and Peninsular Malaysia during the northern winter. Swiftlets' nests are small, shallowly cup-shaped, and glued to the wall. They are made of vegetable material held together by glutinous nest cement secreted from a pair of salivary glands under their tongue. All species use at least some saliva in their nests. The renowned edible-nest swiftlet produces a nest consisting of almost pure saliva with a few feathers.

Table 2. Species of East Asian Cave Swiftlets of Genus *Hydrochous, Collocalia,* and *Aerodramus*

Hydrochous gigas	giant swiftlet	Java, Sumatra, Peninsular Malaysia, Borneo
Collocalia esculenta	White-bellied swiftlet	Throughout Southeast Asia
Collocalia linchi	Linchi swiftlet	Java and parts of Sumatra and Borneo
Collocalia troglodytes	Pygmy swiftlet	Endemic to the Philippines
Aerodramus mearnsi	Philippine grey swiftlet	Endemic to the Philippines
Aerodramus infuscata	Moluccan swiftlet	Endemic to southeastern Sulawesi and Moluccan Islands
Aerodramus hirundinacea	Mountain swiftlet	Endemic to New Guinea
Aerodramus spodiopygius	White-rumped swiftlet	Extensive range on islands on Papuasia, Melanesia, and Polynesia
Aerodramus brevirostris	Himalayan swiftlet	From Nepal and northeastern India to southwestern China, northern Lao PDR, Myanmar, and western Thailand
Aerodramus whiteheadi	Whitehead's swiftlet	Endemic to the Philippines
Aerodramus nuditarsus	Bare-legged swiftlet	Southern and southeastern New Guinea
Aerodramus orientalis	Mayr's swiftlet	Two locations on Melanesian Islands.
Aerodramus salanganus	Mossy-nest swiftlet	Endemic to Greater Sundas (Sumatra, Java, and Borneo)
Aerodramus vanikorensis	Uniform swiftlet	Philippines, eastern Indonesia, New Guinea, and Melanesia
Aerodramus pelewensis	Palau swiftlet	Endemic to Palau Islands

(Continued on next page)

Table 2. *(continued)*

Aerodramus bartschi	Guam swiftlet	Endemic to the southern Mariana Islands
Aerodramus inquietus	Caroline swiftlet	Endemic to the Caroline Islands
Aerodramus sawtelli	Sawtell's swiftlet	Endemic to the Atiu Islands in Cook Archipelago
Aerodramus leucophaeus	Polynesian swiftlet	Endemic to Polynesia
Aerodramus maximus	Black-nest swiftlet	Throughout Southeast Asia
Aerodramus fuciphagus	Edible-nest swiftlet	Andaman and Nicobar Islands, coastal Southeast Asia, southeastern Hainan coast, Indo-China, islands off Peninsular Malaysia Greater Sundas the Philippines
Aerodramus papuensis	Papuan swiftlet	Endemic to New Guinea

The colonies of most swiftlet species are found in the dimly lit parts of caves, relatively close to the entrance. They also readily occupy such man-made structures as abandoned buildings, tunnels, eaves, and coverts of ceilings. Several species, however, can navigate through pitch darkness by echo location, and prefer the deepest parts of caves in which to nest. No other bird except the Oil-bird from South America has this capability, although it may be that the rockfowl *Picathartes* of central Africa finds its way around the dark zone of caves in a similar manner. Unlike the high-pitched sounds produced by bats, the frequencies of the echo-location calls of swiftlets can be heard as a series of clicks in rapid succession, culminating in a staccato rattle. Calls can be heard as soon as a swiftlet approaches the cave entrance. When the swiftlet is negotiating a bend in dim light, or approaching a wall or its nest, the frequency of clicking increases to give a clearer "picture."

Numbers of swiftlet species and endemism. Altogether, 26 species of swiftlets range throughout the tropical Indo-Pacific region from the Seychelles to the western Pacific. A few are common and widespread, such as the white-bellied swiftlet, the mossy-nest swiftlet, the black-nest swiftlet, and the edible-nest swiftlet. Most species are local or regional endemics.

A Day in the Life of Swiftlets

Swiftlets leave their roosting cave at dawn, to flutter and glide above the forest canopy or meander around the edge of the forest vegetation nearby, foraging for the insects that they take in flight. When the sun comes up, they move toward a river and forage above the vegetation along the banks, until they disperse around midday. They may fly long distances: swiftlets have been observed 27 kilometers from their roosting cave. Returning swiftlets begin to arrive in the vicinity of their roosting cave one or two hours before twilight, but they are still swirling high in the sky. They often assemble in large flocks over water, then skillfully glide down and skim over the surface of the water, drinking in flight. At the lowest point of their dive, both wings are swept upward while their bills dip down to flick up a mouthful of water. Occasionally, a clumsy individual will hit the water hard before taking to the air again. After the afternoon splash, the swiftlets retreat to their roosting cave, unleashing a crescendo of clicks while whirling near the entrance. As dusk falls, streams of swiftlets enter the cave to roost; carefully avoiding the emerging bats.

The outward flight continues even when there is a drizzle, and is delayed only if there is a heavy downpour. If rain persists for several hours, the swiftlets will brave their exit from the cave as soon as it has subsided a little. A late start usually means a late return, dashing into the cave speedily, without revolving around its entrance. When a thunderstorm is imminent during the afternoon, the swiftlets will return earlier than usual.

Inside the cave, the squeaking, chirping, and staccato rattle calls of thousands of swiftlets frantically swirling in search of their roosting sites within the confinement of echo-bouncing cave walls, produce a cacophony. Cave swiftlets roost in pairs. The nest site serves as a roosting place. If a nest is present, both birds sometimes snug inside or one clings to the outside the nest. If no nest is present, both will cling side by side on the uneven surface of the cave wall. Squabbles about nest sites are common. If the second of a pair tries to alight, the bird already roosting will squeak and peck until the mutual bond is established. Afterwards, one will help to preen the head and neck of its partner while chirping softly. The breeding cycle is long, three or four months elapsing from the start of nest construction until the nestlings are ready to fledge.

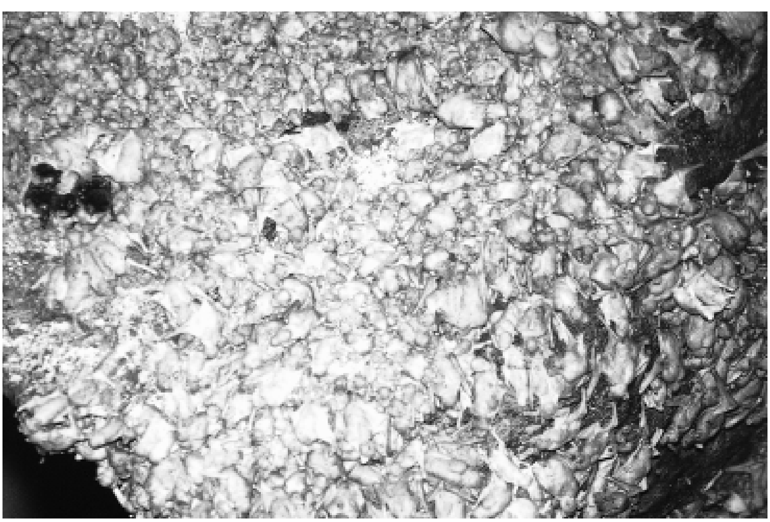
Bats and Caves

In the minds of many people, bats and caves are intimately associated. Indeed, many of the almost 1,000 species of bats inhabiting the world choose caves for a home (see table 3), either in limestone (by far the most numerous) or in other rock. In the tropics, a single cave may house a dozen or more species. In fact, in East Asia, caves harbor more bats and bat species than any other type of roost. Bat colonies may number hundreds of thousands to millions of individuals, and in East Asia, such colonies are found exclusively in caves. The bats use the cave to roost during the day and forage outside during the night. Each bat has its own place in the cave to roost, and more often than not returns to the same cave throughout its life. In the reproductive season, males and females of a particular species may form single-sex groups, and the females then form maternity colonies.

Even in the subtropics and tropics of East Asia, several of the bat species living at higher altitudes (more than 800 meters above sea level) can enter a state of torpor to save energy—for example, during periods of food scarcity. In northern East Asia, where winters are severe, bats use caves for hibernation, which may last several months. During such hibernation, the bats' body temperature decreases considerably and they are extremely vulnerable to disturbance: any arousal costs energy, which is vital to survive the cold period.

Bats have few natural enemies: bat hawks, nocturnal birds such as owls, some small carnivorous mammals (including even some other bat species), snakes, and some insects. Birds and bats may catch bats during flight. Other animals may snatch them from their roosts. Cave floors and walls may be inhabited by various arthropods that eat bat carcasses and also attack living young bats that have fallen from their roosts.

Figure 6. A nursery of hundreds of bent-winged bats in a cave in North Sulawesi, Indonesia. The young are left here while the mothers hunt for food. (photo by Tony Whitten).



Bat biodiversity. Bats are mammals. Biologists divide bats into two groups: the generally small insect-eating bats and the often large fruit-eating bats. Some insect-eating bats have specialized on other prey animals, and some "fruit" bats eat pollen and nectar rather than fruit. An educated guess of the numbers of East Asian bat species using caves for roosting is 262, among which there are 237 insect-eating species and 25 fruit-eating species. Some species are very common and widespread; others are extremely rare, known from only one or a few populations.

Table 3. Bat Species Known or Expected to Roost in Caves

Country	*Insect bats*	*Fruit bats*[a]
Mongolia	11	0
China	76	2 (3)
Burma	70	3 (4)
Thailand	99	4 (7)
Lao PDR	38	2 (3)
Cambodia	28	2 (3)
Vietnam	49	2 (3)
Malaysia (incl. Brunei)	95	6 (9)
Singapore	14	2 (3)
Indonesia	110	19 (21)
Philippines	45	4 (5)
Papua New Guinea	51	8

Note: Many inhabit more than one country.
a. Numbers in parentheses: including occasional cave inhabitants.

Other Vertebrates

East Asia has few nonflying mammals that are primarily associated with limestone. The threatened François's leaf monkey, *Trachypithecus francoisi*, is found in southern China, northern Vietnam, and the Lao PDR and appears to be restricted to limestone hills. The serow, *Naemorhaedus sumatraensis*, a black wild mountain goat, is most often found in limestone areas in East Asia but occurs in other mountain areas in the Himalayas in the west of its range. Among the birds, only the sooty babbler, *Stachyris herbertsi*, which is endemic to central Lao PDR, and the limestone wren-babbler, *Napothera crispifrons calcicola*, of Saraburi Province, Thailand, are found exclusively on limestone outcrops. The bat hawk, *Macheiramphus alcinus*, is a widely distributed species frequently seen diving at bats as they swarm from their caves at dusk.

Figure 7. Small but Fussy: A Rare Cave Bat

Kitti's bat (also known as the bumblebee bat), *Craseonycteris thonglongyai*, is the world's smallest mammal, weighing barely 2 grams and with a length of only 3 centimeters. When it was discovered in 1973, it had to be placed in an entirely new family because it had no known relatives. It is known from 21 of the many available caves all located in forested areas of Sai Yok National Park, Thailand. The bat feeds above the canopy of orchard and other trees. It is extremely fussy about its roosting environment and chooses caves with narrow specifications. This bat is threatened by changes in its roost environment that are due to deforestation, hydrological changes, and other forces.

Kitti's bat (*Craseonycteris thonglongyai*). (photo by Dean Smart, courtesy of Sarakadee Press, Bangkok)

Figure 8. Delacour's langur, *Trachypithecus francoisi delacouri*, is known from only 10 small and isolated limestone areas in northern Vietnam. (illustration by Stephen D. Nash, Conservation International)

At this point, only three limestone-associated reptiles are known in East Asia: a gecko, *Cyrtodactylus cavernicolus*, from Niah Cave and from a gorge in Mulu National Park, both in Sarawak, and a skink, *Lygosoma khoratense*, from Saraburi Province, Thailand. The snake *Elaphe taeniura* is often found in the lighter parts of caves in Southeast Asia, where it catches bats while wedging its tail into crevices in the cave wall.

Flowering Plants

Features of limestone vegetation. Limestone vegetation is unique in many respects. Its appearance and species composition are distinctive compared with other vegetation types. The number of species found is extremely high, particularly when measured per unit of area, and so is the concentration of endemic species, which includes many species of economic value.

Because of the shallow soil often overlying limestone bedrock and soils that are generally deficient in several important nutrients, the vegetation in limestone areas often has a rather straggly appearance. Many of the trees are small, twisted, and gnarled, with sparse crowns. This is particularly obvious where limestone vegetation is surrounded by high tropical lowland forest.

The tallest trees on limestone can reach 30 meters in height, but these are scattered individuals and are generally found in gullies or on slopes where there is deeper soil. As a source of timber, they are a nonrenewable resource because of the slow growth of these trees to attain commercial size. This, commercial-size trees of burretiodendron in China, vitex trees from molave forest in the Philippines, and agathis and teak in monsoon areas with limestone in Java and Sulawesi are not exhausted, except for very remote and inaccessible areas.

An incomplete tree canopy reaches about 15 to 20 meters in height, and common tree families include Euphorbiaceae, Leguminosae, Moraceae, Meliaceae, Sapindaceae, and Anacardiaceae. However, species composition varies from region to region.

Conspicuous and attractive, stout cycads, low fan palms, and, in the more tropical regions, pandans can be seen perched on the jagged edge of the towering cliffs. This is also the habitat of the very rare slipper orchids (especially *Paphiopedilum* spp.). In tropical regions, lithophytes (plants growing on rocks) and epiphytes (plants growing on other plants), particularly ferns and orchids, add to the richness of the limestone flora. The lush herb community around the base of the cliffs rivals any botanic garden rockery in its variety and beautiful species, many of which belong to groups well known as ornamental plants, such as begonias, balsams (*Impatiens* spp.), orchids, and relatives of the African violet

(Gesneriaceae). Many of these herbs are extremely rare and limited in distribution; some known from only a single hill. Hill summits at about 1,000 meters' altitude are often covered with dense, shrubby vegetation. Deeper soils between limestone hills and in pits and dolines may support some high, usually species-rich, forest. The more gentle slopes may support scattered tall trees.

Plant Adaptations to Life on Limestone

The shallow soils, free-draining nature of the rock substrate, and exposure to full sunlight subject plants to severe water stress and high temperatures, particularly in dry periods. Plants on limestone show several adaptations to overcome this:

- Figs that grow on the summit and cliff faces produce an extensive root system that forces its way into fissures and cracks to tap water sources deep within the rock.
- Tropical karst typically supports plants representing different life forms but with succulent leaves that have the same kind of photosynthetic pathway as many desert plants. These include shrubby *Euphorbia* spp.; many lianoid *Hoya* spp.; herbaceous, terrestrial, and epiphytic *Peperomia* spp.; and numerous lithophytic and epiphytic orchids.
- Certain carnivorous plant species occur in extreme habitats, usually those with very acid soils. Typical among these is in the pitcher plant (*Nepenthes* spp.) that also occurs in extreme calcic environments.
- Many woody species are deciduous, with large, thin, short-lived leaves, and avoid drought by storing water in their stems and maintaining photosynthesis via a green outer- or underbark (*Gyrocarpus, Hernandia*). Other, evergreen species such as *Syzygium* tolerate drought by having small, long-lived leaves and often smooth stems, as well as green photosynthetic bark.
- Shallow soils on karst also support many plant species with secondary metabolites (chemical products that are not primarily required for photosynthesis or respiration) that are often toxic to leaf-eating mammals and insects such as moths and butterflies. Some are widely exploited for their medicinal value, including *Canarium, Cycas, Strychnos,* and many species of Asclepiadaceae, Apocynaceae Ebenaceae Rubiaceae, and Simaroubaceae.
- Plants of the genus *Boea* and *Paraboea* are characteristic of cliff faces. They have leaves that can tolerate extreme drought by rolling up to expose the thick silvery hairs on the underside. These reflect light and insulate the leaf from high temperatures. In wet weather, the leaves unroll, revive, and resume growth. Several species of the fern *Doodia* are also similarly capable of rehydrating rapidly after drought.
- Some plants cope with dry periods by dying down and entering a state of dormancy. This group includes plants that have tubers buried deep in rock crevices, such as the elephant yam *Amorphophallus* spp., or fleshy

(Continued on next page)

herbs, such as *Chiritas* species that survive as seeds, readily germinating once the soil becomes wet again.

- Tough, rosette-leafed plants, such as cycads, palms, dracaenas, and pandans, survive drought without wilting. Some *Pandanus* species also exhibit aerial or adventitious rooting and photosynthetic stems.
- Many of the species with specific adaptive features exhibited by plants in karst environments are also found in shoreline habitats and in some extreme, fire-prone, forest-grassland transition zones in dry, seasonally dry climates. Typical species assemblages are included in the genera *Amorphophallus, Cycas, Casuarina, Cerbera, Cochlospermum, Diospyros, Gymnostoma, Gyrocarpus, Tacca,* and *Pandanus.*

Not only does the limestone flora differ in appearance from that of the surrounding forest, it is strikingly different when the species are compared. In the first place, this is due to the unique prevailing conditions: limestone provides a habitat for species that grow on rock surfaces and species that can withstand periodic water stress. The incomplete tree canopy of limestone vegetation also allows the growth of shade-intolerant species, which are excluded from the surrounding tall forest. Interestingly, there is no evidence that many of these plants actually require an alkaline or chalky soil; rather, they tolerate it.

On summit plateaus, leaf litter may accumulate over the limestone to form a layer of acid peat that isolates the plants growing on it from the alkaline bedrock. This peat often supports a suite of definitely acid-loving species, such as camellias, rhododendrons, and carnivorous sundews and pitcher plants.

The varied topography of many karst areas, often in combination with intricate patterns of substrates (from bare rock or talus to a thick soil layer) and degree of exposure, creates a wide array of microhabitats and, as different species are adapted to specific niches, results in extreme species richness. For example, in China's Zhuang Autonomous Region, the limestone areas support a much higher percentage of southern tropical species (88 percent) than adjacent nonlimestone areas, many of which reach the northern limit of their range. In northern Thailand, limestone areas are the southernmost locality of many temperate species, and in Peninsular Malaysia, limestone areas are the southernmost locality for several Indo-Chinese plants.

Biodiversity and biodiversity value of the limestone flora. Compared with other vegetation types, limestone flora are among the richest in terms of species numbers, especially when the comparison is made per unit area. Unfortunately, apart from Peninsular Malaysia, there is no country in Asia where sufficiently complete data are available to know the number of species that grow on limestone (see table 4). Figures from Peninsular Malaysia are striking: 13 to 14 percent of the total seed-plant flora are found on limestone, which covers a mere 0.3 percent of the land area. Besides, the species composition differs from hill to hill, and no single hill is home to more than 20 percent of the total limestone flora of Peninsular Malaysia.

Table 4. State of Knowledge of the Flora of Limestone Areas in East Asia

Country	*Region*	*Status*
Cambodia		No publication available
China	Zhuang Autonomous Region	Summary of conservation value
	Xishuangbanna	Vegetation study
	Guilin	No publication available
Lao PDR		No publication available
Thailand	Doi Chiengdao	Floristic survey
	southern Thailand & islands	No publication available
Vietnam	Cuc Phuong	Floristic survey
	Hon Chong-Ha Tien	Floristic survey
	Other sites	No publication available
Malaysia	Peninsular	Almost complete checklist
	Sarawak	General account
	Sabah	Preliminary account
Philippines	Palawan	General account
	Other islands	No publication available
Indonesia	Sumatra	No publication available
	Kalimantan	No publication available
	Java	Brief account
	Sulawesi	Brief account
	Lesser Sunda Islands	Brief account
	Moluccas	No publication available
	Irian Jaya	No publication available
Papua New Guinea		No publication available

Endemism. A large number of endemic and rare species are entirely restricted to limestone—some are even confined to a single limestone hill or a group of neighboring hills. Many of these endemics have commercial value as ornamentals, such as the much sought-after slipper orchids, balsams with flowers that span a spectrum of colors from white through peachy pink to bluish purple, begonias prized for their variegated and variously shaped foliage, and aroids for those who relish the bizarre—not to mention the cycads and palms. In some cases, even entire groups of plants are characteristic of limestone areas, such as about 30 species of camellia in China, or begonias in Malaysia. They are characteristic either because many species grow together in limestone areas, or because the whole group is confined to limestone areas, with no species growing anywhere else.

Endemic Plants on Limestone

Several groups of plants are notable because they include a large number of species that occur entirely restricted to limestone. They are often known from only one or a few limestone hills, and they include some extremely attractive species that have horticultural potential because of their beautiful flowers or leaves.

- The delicate balsams grow in damp conditions around the base of limestone hills. Throughout East Asia, endemic species occur on limestone, including several species new to science. The Gouty balsam, *Impatiens mirabilis,* endemic to Peninsular Thailand and northern Peninsular Malaysia, is a remarkable balsam with a fleshy trunk and a tree-like canopy.
- Begonias grow in a variety of habitats on limestone, from the damp and shaded base of the hills to crevices in cliff faces and, in Borneo, even on the exposed summit. *Begonia keithii,* known only from a single hill in Sabah, Borneo, has beautiful lacquer-red stems and carmine, heart-shaped male flowers.
- *Paraboea* is a genus almost entirely confined to limestone. *Paraboea brachycarpa* is characteristic of sheer cliff faces. Many species have silvery leaves and produce pretty purple flowers.
- The genus *Monophyllaea* is remarkable because, as the name suggests, the plants produce only a single leaf during their entire lives.
- Three new limestone genera endemic to Peninsular Malaysia have recently been discovered. Each is at present known from a single species. One of the species, *Spelaeanthus chinii,* occupies a very narrow niche: it grows only on dry cliff faces around cave mouths at the base of limestone massifs.

In Peninsular Malaysia, more than 10 percent of the limestone flora comprise species endemic to limestone areas. The numbers for some plant groups per East Asian country are recorded in table 5. These numbers are certain to increase, because many of the limestone areas there have yet to be explored botanically, and many specimens remain unidentified. Many species new to science can also be expected. It is important to note how restricted many endemics are in their distribution. The great majority of the endemic species are herbs. (Woody plants tend to be more widespread.)

Table 5. Species Endemic to Selected Limestone in East Asia

	Southwestern China	*Northern Thailand*	*Lao PDR*	*Southern Vietnam*	*Peninsular Thailand*	*Malaysia*	*Borneo*
Slipper orchids	6	5[a]	0	1	3+1[b]	1[b]	3
Paraboea	1	0	1	0	7+2[b]	14+2[b]	10
Chirita	1	0	0	2	7+2[b]	2[a]	2[b]
Amorphophallus	0	1[a]	0	0	3+3[b]	3[b]	2
Balsams	?	3	?	?	1+2[b]	5+2[b]	3
Palms	1	0	0	1	2+1[b]	1+1[b]	0

Note: No species from Cambodia are recorded. High levels of endemism can also be expected from limestone in Sumatra, Palawan, and New Guinea when their flora are better known.

a. Species on limestone in southwestern China and northern Thailand.

b. Species on limestone in southern Thailand and northern Peninsular Malaysia.

Lower Plants: Bryophytes

Bryophytes are small, ancient plants that can be divided into two groups—the true mosses and the liverworts—both of which have a life cycle divided into two phases. Many species contain chemical compounds that protect them against predation by most insects, snails, and so forth. They also display a variety of growth forms: some produce creeping stems, fixed to the substratum with rootlike outgrowths, and others grow like leafy poles or miniature trees and shrubs.

Weathered rocks (and mortar-brick walls) around the world, but especially in moist climates, are substrates on which numerous different mosses can be found. In tropical limestone areas, various habitats harbor distinctive moss flora, such as plateaus, talus slopes, gullies, cliffs, and vertical slopes that have differing exposures to sun, winds, and rain. Some limestone mosses can withstand the temperature extremes of bare sun or, at high altitudes, frost. To protect themselves against desiccation, they curl up their leaves, then expand them again during a shower. Other species can survive only in permanently cool and wet places; these prefer overhanging wet rocks or deep, shady gullies. Species may display a preference for loamy soils fertilized by phosphates leached out of guano piles; some of these retain water in moisture pouches at the base of their leaves. A few species grow only along calcareous springs or below dripping stalactites in dim light near cave entrances. Special adaptations to deal with excess limestone dissolved in water also exist, with some species able to excrete calcium. Mosses preferring an acid soil may grow in abundance in waterlogged bogs on limestone plateaus without sufficient drainage.

Only a few moss species are known solely from limestone substrate. Most species display a much less marked preference for limestone or are indifferent to the substrate on which they grow. In fact, the moss flora of limestone hills are most clearly defined by the absence of the many species that cannot tolerate high levels of calcium in their substrate.

5

Archaeological, Geological, Aesthetic, and Cultural Values

Archaeological Values

In the early part of the 20th century, geologists working in Malaya, Indo-China (Vietnam), and the former Netherlands East Indies (Indonesia) recognized the value of limestone caves for investigating the cultural history of the region. Their pioneering work has been taken up with enthusiasm by professionally trained archaeologists. They see the importance of such sites for promoting a sense of national and ethnic identity through the demonstration of the modern nation's ancestral occupation of a homeland.

Archaeology of the karst areas—a comparative perspective. Casual discoveries and careful excavations in the region's many limestone caves have played a highly significant part in documenting the history of humanity in the Asian equatorial tropics. The information available now ranges from the late Pleistocene to the mid-Recent period (from about 40,000 to 5,000 years ago) in the fertile and developed regions and until quite recent times in more remote areas.

Elsewhere, in the Middle East and many parts of the Americas, early farming villages were relatively permanent settlements of stone and mud-walled houses built on the ground. Cycles of decay and rebuilding over many generations led to the formation of tells (mounds) that trapped and preserved broken pottery and tools, plant and animal remains, hearths, and often entire domestic spaces. These tells also served as burial sites of successive generations; the deceased were often placed under the house floors.

In the humid tropics, however, settlements moved rather frequently, and most houses were built of wood with floors well above ground level. The debris from these households is scattered and decays rapidly, rather than being preserved. Excavation of Neolithic villages in the humid tropics usually yields little data for reconstructing the lives of early peoples.

In contrast, cliff-foot caves in limestone karst towers, which were easily accessible from fertile land for cultivation, frequently remained in use for various purposes. These caves provide ideal conditions for the preservation of organic and cultural materials. Cave sediments serve as fairly permanent containers for tools, food remains, and other material residues of past communities. Even fossilized remains of extinct hominid species, as well as remains of modern people, have been found in cave deposits. In some regions, caves also contain prehistoric rock paintings and engravings, log coffins and ceramic urn burials of the late prehistoric Iron Age (about 500 BCE to 200 CE), and significant Buddhist shrines of the mid first millennium CE.

Archaeological importance of caves. In East Asia, cave deposits are often the only source of archaeological information for the transition from hunting and collecting to an agricultural way of life. Thus, they are crucially important in the reconstruction of past social and economic history. For this reason, the archaeological data that can be obtained from caves in East Asia are even more important than those obtained from similar structures in temperate parts of the world.

Examples of Archaeological Features Found in Karst Areas

To emphasize the widespread occurrence of archaeological remains, examples are listed below for a selection of countries. In fact, these sites represent only a small sample—any cave that provided good shelter was probably used, occasionally or permanently, by early humans. Archaeologists prefer excavating stratified deposits and tend to pay less attention to evidence of casual visiting by early humans.

Vietnam. Numerous caves and rock shelters in the limestone of Hoabinh and Bacson Provinces, respectively, south and north of the Red River, have produced the earliest in situ sequence for human occupation of the heartland of the modern Vietnamese nation. The sites were first recognized by French geologists, and research of national importance is still being conducted there. The drowned karst towers of Ha Long Bay (Quang Ninh Province) also contain caves—mainly in different locations from the well known tourist sites—that preserve the remains of human occupation from more than 15,000 years ago, when the sea level was much lower and the towers stood in a forested plain drained by fast-flowing rivers. The Soi Nhu culture of these sites has only recently been recognized by Vietnamese archaeologists, and basic survey and excavation have barely started. Some islands (for example, Hon Vung Ba Cua) also contain red-ochre rock paintings that are probably of prehistoric age and the first so far known in Vietnam.

Thailand. The Spirit Cave (Tham Phi), in Mae Hong Son Province in northwestern Thailand, was excavated some 30 years ago. It has produced important evidence of a range of plant foods eaten by the occupants 10,000 years ago. Although damaged by treasure hunters, it is in a remote area and is relatively safe from quarrying. However, in central Thailand, the karst towers between Saraburi and Lopburi, and those near Ratchaburi to the southwest, have been devastated in recent years by quarrying for cement manufacture. This caused severe damage to early (7th century CE) Buddhist shrines, which led to protests by conservation-minded local people and people from Bangkok. Limestone along the Thailand-Myanmar border, in the Petchabuan Range of central Thailand, and the cliffs overlooking the Mekong River in Ubon Ratchakhani Province, contain galleries of rock paintings, the extent and significance of which has been only recently recognized. The spectacular limestone ridges and towers that run down the western border of peninsular Thailand and into Malaysia, sometimes as offshore islands, include Phang Nga National Park and many islands of outstanding beauty, which have archaeological sites that are as yet barely investigated. Lang Rongrien is the only one that has been well excavated, with published results. In addition to its evidence of prehistoric occupation, Thailand is particularly important for its Iron Age log coffins and sculpted Buddhist shrines.

Figure 9. Teak coffins from 2,200 years ago in Bor Khrai Cave, northwestern Thailand. Preservation of the wood in the stable cave atmosphere is excellent. (photo by Dean Smart)

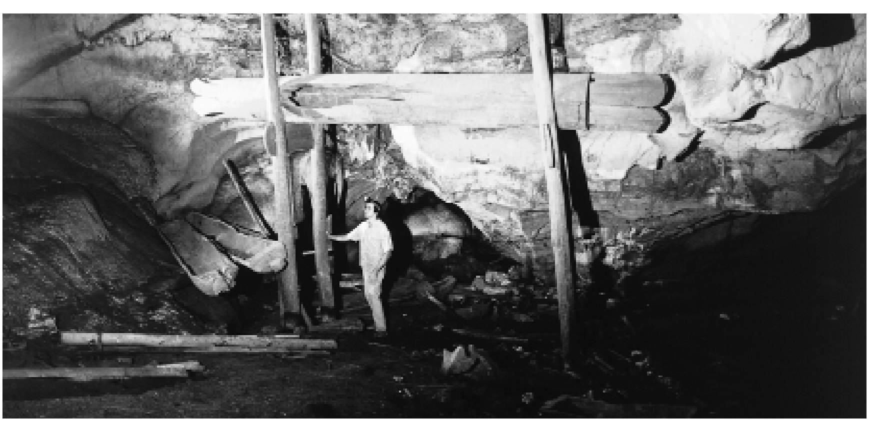


Figure 10. Paintings from a rock overhang in the upper Kwal Yai Valley, Kanchanburi Province, Thailand, showing people carrying a bronze drum, possibly for ceremonial purposes. (photo by Ian Glover)

Cambodia. Laang Spean Cave in Battambang Province is one of the few well-excavated prehistoric sites in the country. Visitors can still expect to find the archaeological trenches opened by Roland Mourer in the 1960s still more or less as they were left. The cave has yielded important evidence for the transition to a settled agricultural way of life.

Malaysia. There are many archaeologically important cave sites in Malaysia. In the Peninsula, Gua Cha is the best known and protected against commercial destruction by its relative isolation. Next to this, the recently excavated Gua Gunung Runtuh yielded a late Palaeolithic burial with the earliest more or less complete skeleton in East Asia, known as Perak Man. However, most of the more accessible cave deposits in Peninsular Malaysia have been—and, in some cases, continue to be—dug out by phosphate collectors. The Great Niah Cave of Sarawak is internationally known and now a major tourist attraction, regularly visited and filmed because of both the spectacular birds' nest collections and its 40,000-year-old sequence of human occupation. The caves of the Madai-Baturong region of Sabah have yielded important new evidence of human behavior and culture over many thousands of years.

Perak Man

Excavations in the early 1990s, conducted by archaeologists of the Universiti Sains Malaysia, Penang, Malaysia, at Gunung Runtuh, Perak, uncovered the remains of a burial at the base of a sequence of occupation deposits. Dated at about 10,000 years old, it is the oldest dated burial including a complete skeleton from western Malaysia, and it was hailed in the local press as the “Perak Man—the earliest Malaysian.” However, this claim is not justified because still older remains of human occupation have been found in Sarawak.

The Philippines. The caves on Tabon Point, Palawan, have been recognized as being of national importance, and others in the Cagayan Valley of northern Luzon, on islands in the Visayan group, and in Cotabato Province, Mindanao, are known to be sites of early human occupation as well as urn burials from the Iron Age. Most, however, are poorly documented. Many other caves throughout the Philippines and central Indonesia contained Iron Age urn burials, often beautifully decorated, marking the earliest known art of the region.

A Cave Full of Jars

In the early 1990s, Philippine archaeologists heard of the discovery of hundreds of jar burials in Ayub Cave in Cotabato Province, Mindanao. Because the cave was in an area controlled by Muslim separatists, research was difficult, but after difficult negotiations, a team from the National Museum was able to excavate and reconstruct many of the burial jars, which dated from the late prehistoric Iron Age, more than 2,000 years ago. Many jars represent individuals, no doubt the people whose remains were buried in them. The finds at Ayub Cave are one of the most important archaeological discoveries made in East Asia in recent years.

Indonesia. Almost all the islands contain limestone areas with significant archaeological remains—for example, the Barisan Range of Sumatra, the cockpit karsts of Java’s Gunung Sewu, the Maros limestones of southern Sulawesi, and the numerous limestone mountains of Timor. Nearly all have suffered from, or are threatened by, destruction by uncontrolled quarrying and phosphate collecting. Salayer Island and Maros in southern Sulawesi, as well as eastern Timor, have many caves with prehistoric rock paintings that are becoming locally important tourist attractions—especially where they are easily accessible by road. However, these locations have suffered badly from phosphate digging, and others near Pankajene were almost entirely destroyed by quarrying before any systematic survey and excavation could be made. Recently, spectacular cave paintings, suggesting similarities to aboriginal cultures in Australia, were discovered in central and eastern Borneo. Next to this, the numerous limestone areas in New Guinea undoubtedly contain a wealth of information, but research in this area has only just started.

Thousands of Years of History

Excavations at limestone caves in East Timor in the 1960s produced a 15,000-year-long sequence of cultural remains with rich environmental evidence documenting the introduction of many animal species to this once isolated and faunistically impoverished island. Species introduced by people include the cuscus (*Phalanger orientalis*), pig, dog, macaque, a common palm civet cat (*Paradoxurus hermaphroditus*), goat, buffalo, cattle, and, finally, horses in the late precolonial period. A corresponding rich suite of carbonized plant remains was also obtained, which demonstrates the importance of cave entrance deposits for the reconstruction of environmental changes.

Figures 11a and 11b. (Left) View of the excavated trench at Lie Siri Cave, East Timor. (Right) Section through about 7,000 years of deposits at the same cave. The dark grey layer in the center is charcoal-rich and marks the arrival of agriculturalists about 4,500 years ago. (photos by Ian Glover)

Figure 12. Cave painting of an anoa (dwarf buffalo) and hands near Pangkajene, Sulawesi. (photo by Didier Rigal)

Paleontological Interest of Caves

In addition to revealing human remains, some excavations of cave fissure deposits have revealed ancient animal remains. These fossils date from as long ago as 760,000 years (in Thailand) and demonstrate the changes that have occurred in the faunal communities. Some of the species, such as a hippopotamus from Thailand, the giant ape *Gigantopithecus*, stegodont (early elephant), *Homo erectus* (from China), a giant wallaby and a large panda-like marsupial (from New Guinea), and the giant pangolin from Borneo, have become globally extinct. Others, such as the orangutans found in caves in Vietnam and China and the giant panda in China, now occupy a much smaller range.

Figure 13. The extinct pangolin, known from cave deposits in Borneo, in relation to a 1.65-meter person.

Geological Value

If it is not recrystallized to marble, the limestone rock itself, its sedimentology, and its fossil contents are important in helping geologists gather information about the period in which the rock was deposited. For example, the Silurian limestones in Malaysia are very rich in fossils that provide valuable information about the depositional environment.

Once exposed to weathering, limestone outcrops, and particularly the caves, retain information about the succession of climates they have been subjected to. Examples are specific karst features that would not develop under the recent climatic regimen, speleothems, and sediment deposits in concavities in the outside rock surface as well as in caves. The same deposits often also contain rare fossils, that, elsewhere, would have had no chance of preservation. Particularly in tropical climates, limestone outcrops are often the only place where such information can be found.

Aesthetic Value

Many karst landscapes are among the most spectacular landscapes in the world and because of this have major economic value. Indo-China, Thailand, and China are particularly famous in this respect. The tower karst landscapes in southern China have served as a symbol of wild, untamed nature at its most impressive in Chinese art. More generally, karst landscapes are also associated with inaccessible nature and adventurous living: the drowned tower karsts in Vietnam and Thailand have served as the background for several movies featuring pirates and heroes. Karst landscapes and spectacular karst features, such as outsized lapiés (karren), underground rivers, and caves with beautiful speleothem formations, are visited by tourists. Unplanned destruction of karst landscapes will certainly leave future generations poorer.

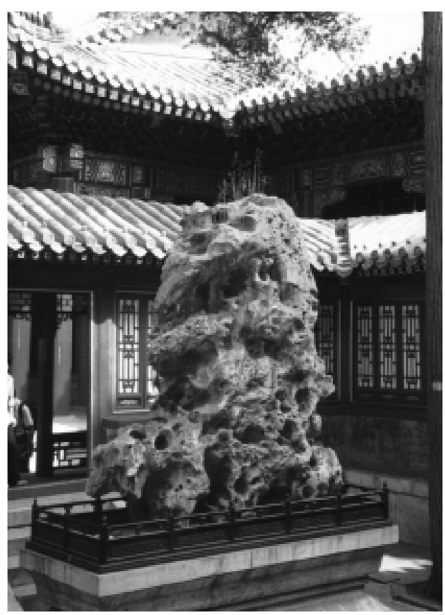


Figure 14. One of many limestone features in the gardens of the Imperial Palace, Beijing. (photo by Tony Whitten)

Aesthetic Considerations in Road Building

Financing from the World Bank was sought by the government of China for a road from Shuiren to Nanning, Guangxi Province, that passed by the magnificent limestone towers of what is known as the "mini-Guilin." World Bank staff, working with staff from Xian Highways University and Guangxi Communications Department, agreed that high priority would be given to selecting the most appropriate route to minimize the spots, volume, and areas of cutting the limestone mountains. Proper mitigation measures would be sought to restore the vegetation and surface characteristics of the rock where cutting was inevitable. In addition, experimental cuts will be made to examine restoration measure and their effects.

Figure 15. (photo by Soichiro Seki)

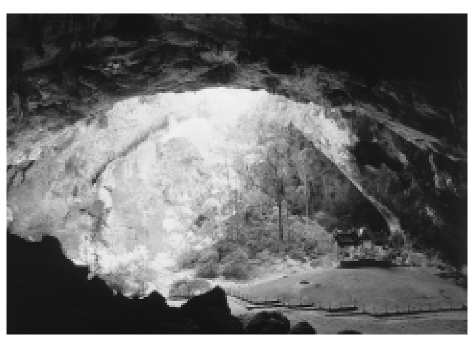


Figure 16. Caves are an important part of Thai culture. This pavilion in Phraya Nakhon Cave, south-western Thailand, was built by King Rama V in 1896 and has also been used by the present King Rama IX. (photo by Dean Smart)

Cultural Importance

Caves seem to be natural places to revere ancestors or worship gods. Active or disused places of worship, temples, and burial caves can be found across the region in and on limestone hills. These places are very important to the local people, and they are regarded as part of their cultural property. Caves may also harbor memorials to recent events of national importance. Many people in Vietnam and Lao PDR, for instance, hold in respect the caves that provided temporary shelter during the recent wars, and many of these have become tourist objects.

In some cases, endemic cave life lives in harmony with cultural uses. In others, temples and other monuments may have a serious impact on their surroundings and on the local biodiversity. Cave entrances may be blocked, and new entrances may be made. This may affect colonies of bats and swiftlets, and all the other life depending on them, and it may drastically change the physical environment. New species may be introduced into the cave system, such as ubiquitous cockroach species, which have a further deleterious impact on the local fauna. Maintenance of the monuments may also include a thorough cleaning of the cave system, including removal of sediment deposits containing paleontological or archaeological information. Plant life, particularly around the base of the hills, is also threatened by the side effects of the presence of temples and cave visitors.

East Asia's Globally Significant Karst Areas

East Asia has two established World Heritage Sites (a status conferred by UNESCO) with important karst features: Ha Long Bay in northern Vietnam and Wulingyuan in China. There are also two recent nominations: Lorentz in Irian Jaya, Indonesia, and Phong Nha in central Vietnam.

Wulingyuan. This area of Oriental deciduous forest lies in Hunan Province, China, and has an altitudinal range of 500–1,250 meters. About one-third of its 38,000 hectares is karstic limestone and has many exceptional physical features, including the world's highest natural bridge, and more than 40 caves, one of which, at 11 kilometers, is one of the longest and largest caves in China. The first know reference to the beauty of the area dates from about 1,300 years ago. The site undoubtedly has more biological interest than is currently recorded.

(Continued on next page)

Figure 17. A view in Ha Long Bay. (photo by Tony Whitten)

Ha Long Bay. This is an area of dramatic, sea-flooded karst towers that draws thousands of tourists each year. There are a variety of important archaeological sites, including some with cave paintings, but until 1998 the biology of the area was virtually unknown. In just 10 days of collecting in Ha Long Bay and neighbouring Cat Ba Island, a team of World Bank and other biologists discovered nearly 100 new species of snails, crabs, fish, and other animals.

Lorentz. This enormous conservation area of 2.5 million hectares in the southern part of Irian Jaya, Indonesia, is exceptional for its wide range of habitats (from glacier-covered Puncak Jaya, the highest mountain in East Asia [5,000 meters] made of limestone, to various forests and swamps to mangroves) and its nine tribal groups. There are huge doline, pyramid-shaped limestone hills, and many caves, most unexplored. It would not be surprising if this area had the world's deepest and longest caves.

Phong Nha. This site is part of an enormous, forest-covered expanse of 400,000 hectares of tropical karst shared between Lao PDR and Vietnam. Culturally import since at least the 9th century CE, the area is becoming increasingly important as a tourist destination. Phong Nha's caves are the longest and deepest in Asia, with a known total length of nearly 65 kilometers. The area is home to Vietnam's smallest minority, the Arem, who until recently lived in the caves.

Figure 18. Coffin being pulled up to a burial cave in Borneo. (photo by John MacKinnon)

“Holy” Crab

On the island of Nusa Penida to the southeast of Bali are two neighboring (and likely connected) caves, one of which, Karang Sari, is used for religious purposes. Karang Sari contains a number of votive altars, which are used occasionally throughout the year and very intensively for special ceremonies. The cave is occupied by insect-eating bats, large whip-scorpions, and a purplish crab that was “discovered” and named only a few years ago. The crab avoids visitors by scuttling across the damp cave floor on its long legs, dropping into drip holes. No other caves are known on the island, and so the species’ global distribution is minute. The cave’s cultural uses and its endemic wildlife thus seem to be in holy harmony.

6

Economic Importance

Limestone is a source of such primary commodities as cement, stone, and lime. The quarrying for these goods is a one-time, nonsustainable use of limestone. Limestone areas also yield a wide variety of products, some of which can be very important to the local economy. The most important is undoubtedly clean drinking water; in fact, 25 percent of the world's population depends on karst-derived drinking water. In addition, karst landscapes often have a large (and increasing) potential for attracting tourists and tourism revenues. Examples of other products derived from the plant and animal life in limestone areas are discussed below. If properly managed, most can be both used and sustained.

The intrinsic value of undisturbed limestone areas, without counting extractable goods, is usually either not considered at all or is severely undervalued because its value cannot be easily calculated. In fact, its value can be estimated only in terms of subsequent economic damage when the effects of the destruction of the limestone area are felt in its surroundings. Undisturbed limestone areas, with all the conditions for the process of karst formation still unchanged, and with all its life communities intact, often have a beneficial effect on their surroundings in both health and economic senses. Therefore, preserving limestone areas and their biodiversity is consistent with UN conventions and a wise way to ensure the durability and health of ecosystems on which human populations depend.

Arthropods

Arthropods have both a positive economic importance as instruments for pest control and a negative importance as pests. Undisturbed and diverse arthropod communities in healthy ecosystems surrounding agricultural land can be a good protection against severe infestations of pests. More generally, arthropod diversity is intimately linked to ecosystem equilibrium. Arthropods play an important role in ecological processes—for example, in the pollination of plants and the decomposition of leaf litter in forests. They are also at the base of many food chains. In East Asia, many animals such as fishes, reptiles, birds, and mammals, which partially or exclusively feed on arthropods, are subsequently eaten by people.

In some areas of East Asia, arthropods from limestone areas are also a source of human food. In Lao PDR and northern Thailand, for example, a range of land and freshwater arthropod species is eaten. These species are not necessarily restricted to limestone, but with the ongoing environmental destruction on the surrounding land, limestone hills become their last refuge. The arthropods are sold in large quantities in the markets in and near limestone regions. In addition, villagers will go to great lengths to remove the nests of large colonies of bees on overhanging limestone cliffs to collect the honey. Arthropods are also used for a variety of traditional medicines; thus, their biodiversity is a potential resource. Plants have long been collected and studied for their medical properties, and arthropods also offer a large potential in this respect, because they are very diverse.

Terrestrial and Freshwater Molluscs

Some large freshwater clams, as well as some large species of land snails, are collected for food. Some of the larger native snail species are so palatable that they are cultivated and exported to Europe, especially Belgium and France. Changes in the composition of the local freshwater molluscs after human disturbance can pose a health hazard to people, because some freshwater molluscs are vectors for diseases affecting people and livestock.

Fishes

For fishes, karst areas are a refuge during the season when outside streams are dry. This is well known to people in Lao PDR, Vietnam, and Sulawesi who fish inside caves—some to a distance of 4 kilometers. Fishes of many species are also caught on a large scale for the aquarium trade.

Swiftlets

Like many bats, swiftlets are insect eaters, catching their prey on the wing. They are efficient fliers and forage over considerable distances outside their roosting cave, helping to control insect populations. Their food includes many species that are considered pests by humans, such as mosquitoes and leafhoppers. Their daily consumption is considerable: it has been calculated that the 500,000 swiftlets at Niah Cave in Sarawak consume about 11 tons of insects daily! Because they return to the cave to roost, their droppings are deposited as guano, a commercial commodity, on the cave floor.

Certain swiftlets also have economic importance because of their edible nests, which are an ingredient in bird's nest soup, an East Asian delicacy. The translucent nest filaments, made of dried saliva, are believed to possess tonic, medicinal, and even aphrodisiac properties. Several species of cave swiftlets use substantial amounts of saliva in nest construction, and their nests are collected and traded in the edible bird nest industry.

Nests of two species have been heavily exploited for human consumption. The most highly prized are those made entirely of saliva, produced by the edible-nest swiftlet. For its weight, the nest of the edible-nest swiftlet is perhaps one of the world's most expensive (legal) natural products This species is widely distributed from the Andaman and Nicobar Islands to China, and from the Philippines to the Lesser Sunda Islands. Nests produced by the black-nest swiftlet contain many feathers. This species is also widespread throughout Indo-China (including Myanmar) and southward to Borneo and Sumatra. The Indian swiftlet also produces nests with a high saliva content, but the trade in the nests of this species became insignificant by early in the 20th century, largely because of overexploitation. The pygmy swiftlet, an endemic species from the Philippines, also produces marketable nests.

With proper management and harvesting strategies, the nests of edible-nest swiftlets can be exploited in a sustainable way, with little if any negative impacts on the biodiversity of the cave. Nest collection can make a substantial monetary contribution to local economies. The nests command the highest price, which for unprocessed nests ranges from US$2,400 to $3,400 per kilogram in Malaysia to more in Hong Kong and other parts of China. The bulk of the edible nests traded around the world come from the black-nest swiftlet. They need to be thoroughly cleaned to remove all the feathers incorporated in the structure. This is a laborious, tedious, and time-consuming task. The processed nests are then rearranged and molded into small pieces of "bird nest." The rewards, however, are considerable: the processed nests can fetch US$1,550 to $2,600 per kilogram in Malaysia, depending on their quality, whereas the raw, unprocessed nests of the best quality sell for no more than US$300 per kilogram.

Bats

Insectivorous bats. Insectivorous bats eat enormous quantities of insects, including those that are harmful to crops, as well as other pests to humans such as mosquitoes and flies. For example, in Papua New Guinea, where copra is an important export product, coconut trees are exposed to a harmful virus spread by the larvae of rhinoceros beetles that lay their eggs in these trees. The local diadem horseshoe bat is a natural enemy of these beetles, and helps to confine this pest.

Another example is found in a limestone cave near Ratburi, where the number of the Asian wrinkle-lipped bat has been estimated at 3 million individuals. Each of these consumes some 7 grams of insects nightly,[5] which amounts to about 20 tons per night for the colony as a whole, or almost 7,300 tons yearly. (Given that one mosquito weighs about 0.0003 gram, it is clear that many billions of insects are consumed each year.) This bat is found in Indo-China, the Philippines, and western Indonesia, and it is a champion colony builder. Anyone who has seen a large wrinkle-lipped bat colony leaving its cave at dusk will be convinced that nature has created here a very powerful, free, environmentally safe anti-insect force. As a bonus, such cave bat colonies produce very large amounts of guano, which can be dug and used or sold as fertilizer.

A Case of Bad Management of Cave Bats

In an effort to control the predation by rousette fruit bats on lychee crops, a government Pest Control Division fumigated bat caves with methylbromide and ethylenedibromide, and later with lindane smoke over a period of 25 years. Ironically, up to 90 percent of all the insect-eating bat species of the country, which all inhabit caves, were killed, while the fruit bat largely survived. This was caused by different reactions of the bats. When fumigation took place, the insect-eating bats would try to hide deep in the cave's crevices and were killed, but the fruit bats would often move out of the cave and return later. Even legally protected species were not safe, because the Pest Control Division was allowed to kill bats in caves in nature reserves. Luckily, the tide turned. There were resulting explosions of moth populations, whose caterpillars destroyed many crops: the ecological function of the bats had been compromised. In the 1980s, the protests of international conservationists against the country's attitude toward nature coincided with the farmers' assessment that while the fruit bat seemed on the increase in spite of the fumigation, the damage to their orchards was negligible or nonexistent. This occurred because they had taken to picking their lychees before they were ripe, as is done in most parts of the world. This happens to be the perfect way to prevent crop damage by bats because bats eat only rsipe fruits, although they may damage some unripe fruits, rendering these unmarketable. From that time on, the bats were left in peace.

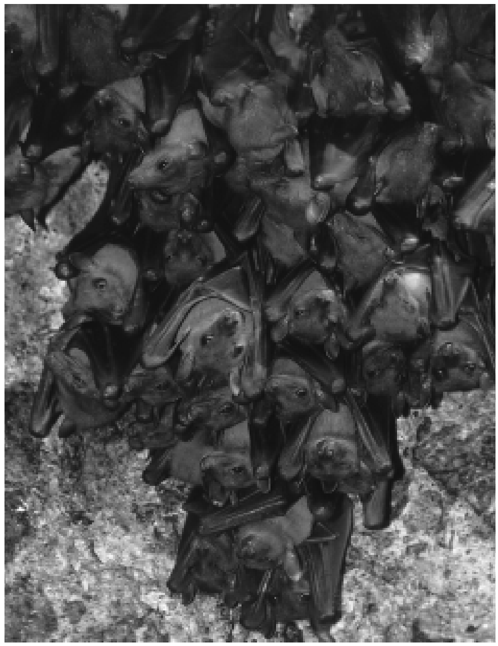
Fruit bats. Fruit bats have different values for people. They eat fruits, pollen, and nectar and thus disperse seeds and pollinate flowers. In East Asia, about 200 different tree species are known to be visited by fruit bats for their flowers only. Some of these and a number of others are visited for their fruits. About 100 tree species, belonging to 32 families, are known to attract East Asian cave fruit bats. It is obvious that many more tree species are involved, as most observations apply to only four bat species: a short-nosed fruit bat, two rousettes, and the dawn bat.

Because many fruiting and flowering seasons are short, the bats have to be adaptable, and some bat species are known to switch from fruits to flowers and vice versa, depending on availability. The fruit eaters often carry fruits away from the tree. Large seeds are dropped where they eat, and small seeds elsewhere, at a distance from the mother tree. This is important for the tree species, because the survival chances of a seedling are much better when it has germinated at a distance from the mother tree. At the same time, the dispersion of the tree species in the forest is promoted. Research on a species of fig tree showed that fruit bats were responsible for the dispersal of 94 to 100 percent of its seeds. The remaining 0 to 6 percent were dispersed by birds, monkeys, and other animals.

The flower-visiting fruit bats serve a large number of tree species. Flying from flower to flower, and eating nectar and pollen, the bats pollinate the flowers. These trees have special types of flowers that are attractive to bats. The flowers are positioned on the outside of the crown so that bats need not enter the tangle of branches and leaves, and they are large and strong so that bats can hang onto them with their claws. They also have a heavy scent and lots of nectar and pollen, and they open at night.

Without bats, numbers of tropical forest tree species would not survive, and the dynamics of tropical forests would be radically altered. Many bat-dependent tree species have economic value on a local, regional, or international scale. Coastal mangrove forests, for example, provide protection against coastal erosion; breeding grounds for fishes, shrimps, and clams; and timber and fuelwood for local use. In parts of their range, important mangrove tree species are pollinated by the cave-dwelling dawn bat. The same bat is also an important pollinator of durian trees, the fruit of which plays an important role in the rural economy of Malaysia and parts of Indonesia and Thailand. As the durian is strongly seasonal, flowering for one month only twice a year, the bats rely heavily on mangrove and other forests and urban garden forests during other parts of the year. The destruction of limestone caves adversely affects the populations of dawn bats and thus the future of mangrove forests and the production of durian. Two other well-known products associated with cave-dwelling fruit bats are petai beans and kapok. The destruction of limestone caves will eventually jeopardize the production of all these and many other commodities.

Figure 19. The cave-dwelling dawn bat, *Eonycteris spelaea,* roosting in the temple cave of Gua Lawar, Bali. (photo by Tony Whitten)



A Multipurpose Bat Tree

The *Oroxylum indicum* tree, called the "midnight horror" in Malaysia, has flowers that open during the night and produce a fetid smell. It is found from India to the Philippines and Indonesia, and it is almost exclusively pollinated by dawn bats, *Eonycteris spelaea*. When a dawn bat lands on a mature flower bud, the impact of the landing opens the five wrinkled and interfolded corolla lobes.

This tree produces a large number of useful products: it is planted as a shade tree; the timber is used to make matches; its roots, bark, leaves, flowers, and seeds are used in local medicine (for example, the seeds as a laxative, and in veterinary medicine); its young shoots, bark, young leaves, and flowers are cooked and eaten as a vegetable in Indonesia; its fruits, both young and mature, are eaten; and its bark and seed pods are used to make tan and black dyes for coloring rattan baskets.

Guano

Guano (dung deposits of cave bats and swiftlets) is rich in phosphate and is generally used as a fertilizer and an organic mulch. In virtually all tropical soils, phosphate is the most limiting nutrient, and although only part of the phosphate in guano is water soluble, the resource is so valuable that local governments license its exploitation, guards are often posted by guano caves, and double barbed-wire fences are erected around the entrance to prevent theft.

Plants

The vegetation as a whole is crucial to the continuation of karst formation, for the storage and circulation of underground water, and for the existence of all the biological communities, including those in caves.

Large trees are usually sparse in limestone areas and, with the exception of a few species, limestone vegetation is usually not of interest to foresters. Local people, however, often extract some timber or fuelwood. Next to this, an array of nontimber forest products is harvested by local people for food, handicrafts, building materials, medicines, and so forth. Many limestone plants (among them members of the Acanthaceae, Araceae, Arecaceae, Asclepiadaceae, Cycadaceae, Orchidaceae, Rubiaceae) are grown as ornamentals, and many others have great potential in this field. Unfortunately, harvesting at present, particularly of the large ancient cycads and slipper orchids, is not sustainable. Ideally, the wild populations would be treated initially as a source and then, once some plants are transplanted to a nursery, further propagation by artificial means would not harm the natural populations.

Slipper Orchids and Limestone

Slipper orchids, many of which are restricted to small areas of limestone, are probably the most sought-after wildflowers on earth. Single specimens of wild collected plants have changed hands for tens of thousands of dollars. Many of these delightful plants end up in privately owned greenhouses to support the self-esteem of the owner, but there is more to the value of this plant. Growing hybrid slipper orchids on an industrial scale, to sell them as cut flowers or pot plants, is a worldwide business, with a yearly turnover of billions of dollars. Properly marketed, a new hybrid with flowers of an unexpected shape or color can bring huge profits. With the 70 species of slipper orchids known so far, the possibilities of creating something really new have been more or less exhausted. In the last few decades, therefore, a quest has been launched for the remaining undiscovered species.

(Continued on next page)

Not surprisingly, overcollecting, next to deforestation and limestone mining, has taken its toll. Many slipper orchids are on the verge of extinction, and some are already extinct in the wild. Limestone cliffs that in the past were strewn each year with the flowers of slipper orchids are now barren or nearly so. The remaining populations should be given top priority when the protection of limestone areas is being considered; a population of slipper orchids on a limestone hill is a strong argument against using the hill for any industrial purpose and for implementing protective measures instead.

A few examples of limestone slipper orchids are:

- *Paphiopedilum sanderianum* (see color plates) is one of the most valuable and spectacular species of slipper orchid, with cork-screw petals reaching 1 meter in length. This species is known from a single population in Sarawak, on the limestone of the Mulu National Park. Although theft of plants cannot always be avoided, the species is relatively safe.
- *Paphiopedilum malipoense* is restricted to seven widely scattered localities in Vietnam and adjacent China, many of which are already depleted. It is found growing close to the top of south-facing limestone cliffs, in hollows in the limestone rock filled with moss and leaf litter. The flowers, which measure 6 to 12 centimeters across, develop in early spring. The species was discovered only 15 years ago. Two other extraordinary, and equally rare, species have recently been found in the same area. All are threatened and probably close to extinction.
- *Paphiopedilum stonei* is restricted to a small number of localities on the limestone ranges south of Kuching, Sarawak. Most populations, which usually grow high on sheer limestone cliffs and slightly shaded by the crowns of large trees, are already badly depleted by collectors, and they are now further threatened by the ever-expanding limestone mining operations in the area. This slipper orchid will not be the only victim; the limestone ranges south of Kuching have an extraordinarily rich and absolutely unique flora and fauna, including 100 or more species of snails that are found nowhere else, as well as the locally endemic pitcher plant *Nepenthes northiana* (see color plates). All are threatened, and measures should be taken before it is too late to provide protection for a carefully selected number of limestone hills in the area.

Tourist Caves

Limestone-related tourism is an important source of local income. For example, 2 million tourists visit Ko Tapoo in Thailand (better known as "James Bond Island," the background of a final shoot-out in a James Bond film), and most of the 7 million tourists who come to Thailand annually have visited at least one cave. Some other major karst areas visited by tourists in the region are the karst towers of Guilin and Yunnan's "Stone Forest" in China; the Niah, Mulu, and Batu Caves of Malaysia; the flooded karst of Ha Long Bay in Vietnam; and Tham Nok Nang En in Thailand. There are also many other, smaller local reserves with caves, temples, local commuters collecting birds' nests, and huge bat roosts that attract tourists.

Early Art for Tourists

The walls of limestone caves and cliff-foot shelters throughout East Asia that were occupied by prehistoric humans are often decorated with hand stencils (such as those below, from Maros, Sulawesi) and representations of local animals and scenes of long-past ritual activities. As with the better known cave paintings of France and Spain, such prehistoric art sites are becoming important tourist attractions for both local and foreign visitors.

Figure 20. Hand stencils from Maros, Sulawesi. (photo by Didier Rigal)

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Threats

Limestone Quarrying

The impact of limestone quarrying may be local, but frequently quarries are extensive; complete hills may be consumed, with the total obliteration of all plant and animal life in just a few years. In addition, various disturbing effects reach far beyond the actual boundaries of the quarry. Much quarrying in East Asia is uncontrolled from an environmental point of view. Extensive areas, which until a decade ago offered the traveller views over fine limestone landscape, are now pervaded with noise, dust, impoverished and whitened vegetation, and silted rivers.

The environmental impacts of limestone quarrying include:

- Limestone dust: This may spread over the surroundings during dry weather, leach into the soil during storms, and exercise harmful effects on the flora and fauna. Modern cement industries have made large strides to control dust emissions.

- Blasting to break up rock: This sets off vibrations and shock waves that cause stalagmites and stalactites to break off and cave roofs to crack or collapse. Even one new crack in a cave may alter the environmental conditions so that cave communities are displaced or killed: light may enter the cave, or streams and ponds may suddenly drain into a crack in the floor. Colonies of bats and swiftlets may be disturbed, so that they leave their roosting sites. This can even occur as far away as 1,500 meters from the quarry if the opening of their roosting cave happens to be in the direction of the blast.

- Partial or total destruction of cave passages: As rock is removed, any cave passage is destroyed, along with any sediments it may have contained. The cave as a habitat will also cease to exist, and only those creatures that are (a) mobile and (b) able to find new homes will survive; the rest will die.

- Disruption of underground drainage: Quarrying may intersect active conduits or cause their blockage, with adverse consequences for aquatic communities.

- Water pollution: Large amounts of silt and other effluents of quarries (waste, fuel, oil), particularly if ore bodies are mined or if small amounts of ore are present in the limestone, may pollute rivers within and far beyond the boundaries of the limestone area, as well as underground water bodies. Rivers in Indo-China, for example, host hundreds of species of large freshwater clams and snails, many of which are site endemic to a section of one stream. Development puts great pressure on these animals, which are very vulnerable because they are easily smothered in mud or killed by chemical pollution when silt from construction or mining activities is allowed to seep into a river. Fish communities are equally vulnerable.

- Collateral damage: Quarry workers have often migrated from outside the local area. They and their families may put stress on the environment around the quarry by fishing, hunting, using water for household purposes, improper waste disposal, collecting fuelwood, or exploiting other resources on the limestone hill to create extra income.

- Loss of natural habitat: This occurs either as a direct result of the removal of the rock or as a result of fuelwood collecting, fire, and so forth. This is covered in detail in the rest of this report.

Large-Scale Changes in the Hydrological System

Underground natural water reservoirs are an important source of clean drinking water. Excessive extraction of water may cause the drying up of aboveground and underground systems in limestone areas, leading to possible collapse as flooded cavities become filled with air. Small water bodies, which may be inhabited by small, site-endemic fish species and snails, will disappear, and with them the species. Alterations of flow patterns by the construction of dams, water extraction, and flood control in and around limestone areas will profoundly change the limestone environment and lead to the extinction of whole communities. The quantity of water and the availability of nutrients change, longitudinal movements and migrations of fish and other species are interrupted, and aquatic habitats are destroyed, especially the temporarily flooded areas that many fish species use as spawning or nursery grounds.

Fire and Other Disturbances of the Vegetation Cover

Because limestone bedrock retains very little rainwater, the vegetation tends to dry out seasonally and is then easy prey to fire, especially in El Niño years. Burning becomes more frequent as agriculture extends toward the borders of a limestone area; fires started by farmers to clear their land set alight the vegetation at the foot of the limestone hills, then sweep up the cliff faces and consume the vegetation on the top of the hill. Limestone vegetation under seasonal or dry climates has a natural resistance to fire and may recover after a while. However, a drought-struck forest in what is usually a permanently wet climate certainly has no natural resistance, and a bushfire may destroy it forever. Thus, fires triggered by unusual climatic events are the most harmful.

A fire in unusually dry rainforest at the foot and on the lower slopes of limestone hills will destroy the vegetation and will also burn the organic soil layer, which, no longer held together by tree roots, is then readily washed away in subsequent rains. All aboveground animal communities will be badly affected, and many will disappear entirely, leaving large limestone areas barren. In some places, such as northern Thailand and northern Vietnam, the original forest is replaced by grasses. Without protection of a tree canopy, the damp, dark conditions around the hill base are lost, together with most of the endemic species, plants and animals alike. For arthropods, a slight disturbance of the vegetation may lead to a temporary depletion of the local biodiversity, but hundreds of arthropod species depending on one particular plant species for food or propagation are inevitably eliminated when the native vegetation is entirely destroyed. Higher up a limestone hill, most soil occurs in rock crevices, where it may be protected from burning. Subsequent exposure to the sun, however, will render these pockets inhospitable to much of the original fauna.

Underground communities also will suffer. If the aboveground vegetation has been removed, the underground formation of stalactites and stalagmites may stop and the cave environment may dry out, affecting cave communities. These impacts may be exacerbated by the clogging of rock crevices that give access to the underground world by a mixture of clay, ashes, and burned remnants of vegetation. This captures water and nutrients, preventing their further descent into underground voids. More directly, swiftlet (and presumably bat) populations in Sabah, Malaysia, have been drastically reduced in numbers by fires in the surroundings of their roosts and by the smoke.

In more seasonal and dry climates, fires occur more regularly and are generally less destructive. Here, the vegetation has a larger ability to recover after burning, and soil fauna in crevices are adapted to survive spells of extreme exposure to sunlight. However, an increased frequency of bushfires will deplete or destroy the vegetation unless there is already a history of episodic fire through which the community has evolved.

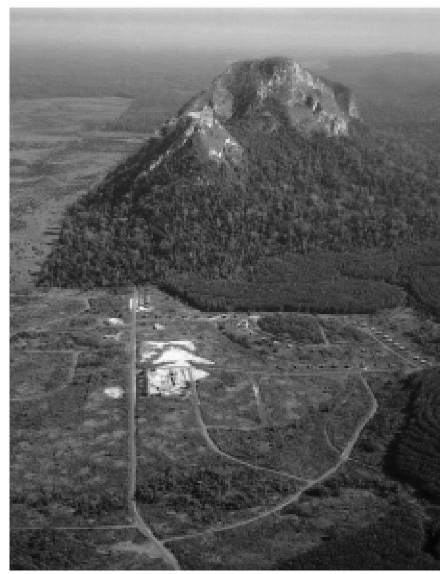


Figure 21. A limestone hill with native forest on its lower slopes in Pahang, Peninsular Malaysia, becoming isolated as plantations develop around it. (photo by Tony Whitten)

Pollution

Next to silt, important sources of water pollution include industrial effluents, mine wastes, fertilizers, and pesticides. These may turn rivers and other water bodies into biologically dead storage basins of waste. Polluted rivers passing through limestone bodies will affect the aboveground environment of the river itself, as well as the environment of its vicinity. Underground, the pollution may have more widespread effects, because the polluted water may spread widely beyond the actual streambed of the river, and it may enter the water table, contaminating the deep groundwater. In many cases, limestone areas have only a very limited cleansing effect on polluted water, because of the fast flow-through rates of the water.

An additional pollution threat may be posed by acid rain, which neutralizes alkaline conditions in limestone soils. There is some circumstantial evidence from Europe indicating that the distribution of certain snails has been reduced as a result of acid rain.

Acid Rain

There is some evidence from Europe that acid rain has had a detrimental impact on terrestrial molluscs. Whether this is through the effects of acid on their shells, or their habitat, or on their food is not known.

Swiftlet Nest Collecting and Guano Digging

The collection of nests and the removal of swiftlet and bat guano are generally conducted under local licenses. In many cases, entrances to caves that are rich in these resources are closed with barbed wire or are jealously guarded against theft. Nest collection is usually subject to strict (often traditional) rules to prevent depletion of this resource, and collectors are often well aware of the importance of the rules and abide by them. In spite of this, and although some cave systems have been exploited in a sustainable way for many years, collecting often causes a considerable loss of eggs and young birds. The digging of guano results in temporary disturbance, but, if conducted with care, is not necessarily seriously destructive in the long term. For example, its impact can be reduced if the guano is exploited only seasonally, in periods when bat maternity colonies, for example, would be less affected. However, the exploitation of fossil guano deposits (phosphate) may lead to the destruction of sediment deposits containing paleontological or archaeological information.

Tourism

Depending on the type and management regime, some cave systems have considerable capacity to sustain tourist exploitation without degradation, such as those with large rivers passing through underground caverns, or where there is strict zoning with sensitive areas off limits to visitors. Others have less capacity: high-energy caves with guano deposits can be exploited for tourism only if measures are taken to ensure the survival of the guano fauna and not disturb the bat or swiftlet colonies on the ceiling. Low-energy caves with numerous pockets of stagnant air, by contrast, are extremely vulnerable, and the first party of tourists, if they are not subdued by the heat, the dampness, and the bad air, may do considerable damage.

Risks that need to be understood in connection with tourism development of caves include:

- Changes in humidity, air-flow patterns, and temperature may displace cave dwelling arthropods and force them to retreat deeper into the cave system.

- Communities of soil-dwelling cave inhabitants, such as arthropods, may be trampled to extinction below tourist feet. Some may retreat to other suitable places, but guano-dependent species, are bound to their guano piles. They cannot move easily, nor can most species switch to a new source of food, which often accumulates rapidly: human garbage.

- Visitors may also introduce nonnative species into the cave that have an impact on local communities. Examples are ubiquitous cockroach species, as well as algae and bacteria.

- Permanent lighting may stimulate the growth of algae, moss, ferns, and other plants, and attract their associated fauna.

- Bats and swiftlets are sensitive to disturbance. Strong light and loud noises should be avoided in their environments. Some species of bats that pollinate commercial fruit and other trees and are important pest control agents may abandon a disturbed cave and leave the area, which could cause both financial and ecological loss.

- Stratified cave sediments can be disturbed by digging or trampling. In some cases, truly drastic measures are taken to make a cave suitable for exploitation, for example, using a high-pressure hose to remove all the cave sediments, including archaeological material and other scientifically important information. Raised walkways in caves should be encouraged wherever possible to avoid the destruction of cave floor features.

- Speleothems are extremely fragile, and are easily stained by dirty hands, soot, or algae that start growing in the light of lamps. Besides, some visitors have an irrepressible desire to deliberately damage or deface them, to paint or carve their names in conspicuous places, or to take souvenirs away from the cave. In parts of East Asia, speleothems are collected locally as medicine or sold as garden ornaments.

- Garbage often accumulates rapidly.

Aboveground, the vegetation cover will suffer first, because limestone vegetation is so very fragile. All life depending on the vegetation will also be affected:

- People climbing limestone hills may irreversibly damage the vegetation in gullies and on rock faces and limestone summits.

- Poorly planned and carelessly constructed paths may cause further damage.

- There is an increased risk that fires may be started by tourists.

All this should be considered when a cave is to be exploited for tourism. The carrying capacity of cave systems should be carefully evaluated. The cave system and its external surroundings should be carefully zoned to ensure that tourist exploitation is restricted to just part of the system. The circulation of visitors inside and outside the cave should be well planned, and the visits should be of limited duration. Litter should be regularly removed from the cave and its surroundings to ensure that the cave will remain a tourist attraction. Facilities for education and recreation should be provided outside the cave to enable waiting tourists to spend their time pleasantly. Visitors should also be protected against the potential hazards of the cave environment, so that they can visit a cave safely.

"Wild caving" by cavers is more difficult to control. Such visitors should adhere to high standards of behavior, have adequate skills to visit a cave safely, and do so without damaging the underground environment. Well-disseminated recommendations from caving clubs or national caving associations would raise awareness of the potential damage that can be wreaked by carelessness. The most serious pollution by cavers is probably the remains of the carbide used in their headlamps.

Hunting

Excessive hunting will eventually deplete wildlife on a limestone hill. Some otherwise pristine limestone areas, which should support rich wildlife communities, are already unnaturally silent to the ear of the experienced visitor: all wildlife is gone. In Vientiane, capital of Lao PDR, the main market generally has dozens of horn trophies from the serow (mountain goat) from limestone areas. Many groups of animals are affected, including less likely groups such as bats. These are found for sale at many local markets, such as at Loei in northeastern Thailand, where various species including the black-bearded tomb bat are eaten, and at Imandi in northern Sulawesi, where the hairless bat and 13 species of fruit-eating bats are offered for sale.

Collecting

Commercial collecting affects only a small number of limestone plants and animals, but in most cases it is an unsustainable and irreversible activity. Large, ancient cycads have become standard garden and landscape plants and are collected from the wild in bulk. In Hanoi, Vietnam, for example, cycads from the nearby Ha Long Bay area adorn numerous gardens and the entrances of hotels and other large buildings. Populations of newly discovered species of slipper orchids in Indonesia, Indo-China, and southern China are collected out by villagers taking advantage of a valued local resource, to be sold for high prices to orchid enthusiasts. Although theoretically protected from international trade (being on Appendix 1 of the Convention on International Trade in Endangered Species [CITES]), collection of such plants continues because there is little or no local enforcement and because much of the trade is domestic. The trade in Thailand has been extensive in the past, but seems to be reduced at least in part because the wild stocks have been so reduced. Rare slipper orchids from China still appear for sale outside the country. This drain on wild populations is unnecessary, because these plants could be propagated artificially. Near a quarry site, this collecting is likely to increase with the arrival of migrant workers in search of supplementary incomes.

Another example is the aquarium trade in curious or attractive cave fish. Here, too, the high prices paid for some species are an incentive to continue the exploitation.

Excavation of cultural remains in caves is illegal in all the countries in the region, but enforcement is lax. Many markets in Thailand offer stone tools, pots, and other items of archaeological interest for sale, some certainly from caves, and ancient pottery is ground up to make Buddhist amulets in the belief that they will impart magic.

Figure 22. Decades-old cycads freshly pulled off limestone hills in Ha Long Bay, northern Vietnam, about to be loaded onto a boat to meet the demand from urban householders for pot- and garden-plants. (photo by Tony Whitten)

Unfortunately, some scientists also have been guilty of significant depletion of local biodiversity. Overzealous collecting of rare or endemic species, destructive collecting methods (for example, fumigation within caves), and poorly planned research are examples of such destructive activities.

8

Vulnerability to Disturbance

The impact of disturbance on the local limestone biodiversity depends on the nature of the disturbance, the type of habitat, and the vulnerability of individual species. Generally speaking, biological communities are particularly vulnerable to novel perturbations—that is, to disturbances to which they have had little previous exposure. Thus, conservation biologists should address novel perturbations at a site rather than assume a hypothetical vulnerability of the local communities. For example, it is useless, or even counterproductive in the long run, to prevent fires in vegetation types under a natural regime of regular burning. The vulnerability of the individual limestone species is determined by various properties such as:

- Range size: Limestone organisms are often restricted to a very small area. A single mining operation can easily lead to the extinction of species.

- Population size: Limestone species often occur only in small populations, particularly those arthropod species living in nutrient-poor parts of caves. The destruction of a small number of individuals can endanger the existence of the whole species if it is locally endemic.

- Specialization: The chances that a particular species will survive a perturbation also depend on its level of specialization, that is, its degree of adaptation to a particular habitat. For example, guano-dependent arthropods have reached such high levels of biological specialization that they cannot switch to another habitat when their native habitat has been destroyed; in fact, they cannot even colonize new sites that are suitable for them but not in direct contact with their original site. In contrast, some aboveground soil arthropods may survive in small pockets of soil and disperse again, once vegetation has reclaimed the denuded area.

Impact of Disturbance

Little is known about the precise mechanisms at work on the local biodiversity during disturbance, but some effects can be inferred from comparison of limestone communities in habitats that are otherwise similar but variously affected by disturbance. Generally speaking, disturbance leads to a considerable loss of species.[6] For example, a survey in Ba Be National Park, northern Vietnam, revealed that a transect through primary forest yielded no fewer than 231 species of butterflies, whereas transects along areas at least partly covered with fairly mature secondary woodland yielded only 116 to 146 species, and along a transect through an area experiencing active disturbance, only 65 species. Similarly, soil samples taken during a survey in East Kalimantan, Indonesia, yielded 29 different snail species along a transect through undisturbed primary forest on limestone, and at most 8 species for transects through secondary forest developing after the devastating bushfires of the last decade.

Extinction of species from the site. For a site-endemic species, severe disturbance of the site may well cause its extinction as a whole. This is by no means only a reflection of theoretical value. In Sarawak, Borneo, six snail species are known only from a limestone outcrop of about 0.2 square kilometer. Clearing and burning the vegetation could destroy these species within a week or so. Recent reviews of the Bornean species of a single snail group brought to light the extinction by habitat destruction of at least four site endemics, and the suspected extinction of three others. In Peninsular Malaysia, at least one species of the same group has suffered the same fate. Also in Peninsular Malaysia, 17 plant species are now extinct; altogether 12 percent of the flora are endangered because the limestone karsts are not adequately protected. Elsewhere, the state of affairs is equally bad, but much extinction goes unnoticed because the species concerned have never been described or even collected. The position of local-endemic species may be endangered by the destruction of a site, without being under threat of immediate extinction, because at least a few populations exist elsewhere. The same usually applies for species that sought refuge on the hill after clearing of the surrounding land.

Skewing of the local fauna. A sheltered limestone outcrop in an undisturbed, densely vegetated environment is often very rich in snail species, but the number of individuals per species is generally low, and no one species occurs in particularly large numbers. A more stressful habitat in the same area—for example, a sparsely vegetated, sea-facing limestone cliff—may harbor an impoverished version of the same fauna with fewer than half the number of species, with some species abundant and others

Living Dead

The well-known India-rubber plant, *Ficus elastica*, is restricted to limestone in the wild. It is a common pot plant in homes and offices, and impressive trees are found in many villages and cities in East Asia, often associated with temples and other cultural sites. In spite of its prominence, it appears to be ecologically extinct, a member of the "living dead" as a consequence of its highly specific pollination system: it is entirely dependent on a single species of minute wasp, which depends in turn on this particular species. The pollinator appears to be extinct as a result of habitat loss and the resulting small and widely scattered populations of this limestone species, and the tree survives only because it propagates so easily from cuttings.

found only incidentally. Disturbance often has a similar effect on other local fauna. Some species are decimated without disappearing entirely from the scene, while others exhibit vast increases in numbers of individuals, often after a pronounced decline. Usually, the narrowly endemic species and the specialized species suffer most; their place is then taken by widespread species that tolerate disturbance. Sometimes a narrowly endemic species may prove surprisingly resilient. For example, a snail species in Sabah, Malaysia, endemic to only a few sites, flourishes by the thousands on a small hill of which only the base remained after quarrying, and which is now overgrown with impoverished vegetation comprising nonnative species.

Invasion of a site by nonnative species. After disturbance, species frequently appear at a site that did not previously occur there. Often, such species are widespread and native in the area, and some of them are agricultural pests occurring near the site and taking advantage of the disturbance. More problematic for the local biodiversity are species that have been introduced from other regions by human activities. A few weedy plant species often settle and overgrow a site within a short time, and a few animal species may suddenly abound. Although some large species may be a bonus for the local human population as food, they add little inherent value to the biodiversity of a site.

The introduction of nonnative species is regarded by IUCN–The World Conservation Union as the second most-important threat to biodiversity after habitat loss. They and their diseases and parasites may further deplete local biological communities that are already under stress. Some of the best-known case studies concern aquatic systems and islands. For example, lake fish communities worldwide, often with unique fauna including many endemic species, have been decimated by introduced species. Within East Asia, the Lake Dianchi basin in Yunnan provides probably the most glaring example of what can happen: out of the 25 indigenous fish species, only 8 are extant, and out of the 12 endemic species, only 4 survive.

In terrestrial environments, the introduction of species can be particularly detrimental to lowland karst forests, which are now of very limited extent in the region. Although many nonnative species invade ecosystems already under stress, such as disturbed sites or quarries, others can invade intact, pristine ecosystems For example, the clothes moth, various cockroaches, and house spiders long ago invaded human dwellings from neighboring caves. The bedbug is thought to have begun its association with people when the two shared caves. These species are now easily transported worldwide and quickly reinvade caves everywhere. An example is the common cockroach, *Periplaneta americana,* which has invaded Malaysian and Thai caves to the detriment of the native fauna. Weedy plants and vertebrates are the most conspicuous invaders, but are not necessarily the most harmful. Many invertebrates and microorganisms can also devastate local biodiversity and severely affect public health and economic well-being.

Humans often inadvertently introduce species through shipments of foodstuffs, supplies, and equipment. Other species are introduced deliberately, for food, ornament, recreation, forestry, or biological control. Once established, introduced species can be *pervasive* (able to disperse far beyond the area of introduction), *permanent* (able to multiply in perpetuity), *injurious* (able to harm native species), and *insidious* (able to affect ecosystems, sometimes in a profound but inconspicuous way). The introduction of nonnative species should never be conducted without very careful examination of the possible ecological (and economic) impacts.

Regeneration after Disturbance

The regeneration of the animal biodiversity on a site after disturbance depends largely on the regeneration of the vegetation cover and the residual fauna. It can take decades for limestone vegetation under a permanently wet tropical climate to recover to a degree where it will support significant populations of native species. This is determined in large part by the time required to develop a new soil layer. Typically, grassland or a vegetation cover of climbers of widespread and nonnative species develops, which may provide some shelter for the remnants of the soil and the original fauna, but which also may displace local species that could otherwise have survived the disturbance. Prominent species on disturbed sites are often bird's eye chilli, the sprawling and aggressive *Lantana camara,* and *Chromolaena odorata. C. odorata* dries out in the dry season and becomes a fire risk, thus perpetuating the cycle of burning. This substantially degrades the biodiversity value of limestone areas, as has happened with numerous hills already. Notwithstanding the negative effects of these two species, they can act as useful soil cover in areas that might otherwise be exposed and *L. camara* in particular is known to have ameliorative effects on soil through its heavy litter fall. Tree planting with native species of mature secondary woodlands may help accelerate the regeneration of the original vegetation by restoring the soil layer and creating the right environment for plants to reestablish on the site. This may succeed if undisturbed vegetation is still present in the immediate surroundings of the site, and especially above it, to act as a seed source. For many groups of limestone animals, monoculture tree plantations are useless because they do not offer the variety of habitats and host plants of the native forest.

Regeneration in aboveground water bodies depends on the scale and the type of habitat alteration. After small-scale impacts (for example, localized pollution), most species may be able to recolonize the affected area, provided that safe and healthy populations exist downriver or upriver and provided that the habitat structure permits it. (For example, if a meandering stream with a diversity of microhabitats is transformed into a concrete channel, no recovery should be expected.)

Invasion by nonnative species is more problematic because if such a species becomes established, it is virtually impossible to eradicate it. No case of successful eradication of an introduced aquatic species is known.

Extinction of endemic species (which in limestone areas is documents for lacustrine species in China) is irreversible and is of special concern in caves and lakes where very specialized species are known. However, in some instances, a species phylogenetically close to an extinct species may exist in another location. Provided that the disturbance is removed in the habitat of the extinct species and the population of the second species is sufficiently healthy and secure, the second species could be used to restock the habitat of the extinct species.

Recovery of cave fauna is not impossible, depending on the degree of disturbance and on the presence of remnant populations of the cave animals in small passages within the rock not accessible to humans. To assist recovery, the removal of pollutants is particularly important, and even the reconstruction of elements of the cave could be considered.

The capacity of the original limestone flora and fauna to recolonize a site after disturbance differs for each species. Although little is known, a general rule is that the most specialized species, which are the first to go, may be the last to return. Actively flying insects or wind-dispersed arthropods (some spiders, for example) may well be the first to arrive, and parthenogenetic (capable of reproduction without male fertilization of eggs) species in particular are good at recolonizing. Wingless soil- and cave-restricted species will have to walk in, which is a slower process. If they are specialists that cannot survive beyond a single habitat (like some guano dwellers), it may take a very long time before individuals arrive by chance on the right spot. Many snail species may have a somewhat higher ability to endure adverse conditions caused by disturbance. Often, the last remnants of the original vegetation cover are crucial to successful recolonization because they serve as refuges for the fauna and the rapid redevelopment of a cover of secondary growth, so that a moist microclimate is maintained.

Disturbance of Sites of Archaeological and Cultural Importance

Unlike biodiversity, archaeological remains are a nonrenewable resource; once they have been disturbed, restoration is impossible. The archaeological record in the East Asian karst regions is seriously threatened by quarrying, the digging of guano piles for phosphates, and tourist exploitation. In the process of these activities, the archaeologically important deposits are seldom recognized, and the ancient remains are annihilated or discarded as refuse. Thus, a finite source of information about our past is often destroyed before it has been scientifically assessed and recorded. The preservation of a good sample of limestone caves in the many different environments and countries of East Asia should be given high priority as important monuments of the region's cultural property.

Culturally important sites such as temple complexes in limestone areas in Thailand, Lao PDR, and Vietnam are in some cases also nonrenewable. If so, they deserve protection, but their maintenance and exploitation—for example, for tourists—often have a considerable impact on the surrounding area.

9

Impact Assessment and Site Selection

At present, the exploitation of limestone for industrial purposes throughout East Asia exacts a heavy toll from limestone environments, their biodiversity, and their cultural and historical value. This need not be so. Limestone is a nonrenewable resource, and the damage caused by its extraction should, in the first place, be reduced by a less wasteful use of cement, so that less is needed. A further reduction can be achieved by using alternative construction materials wherever possible, such as bricks (of mud and laterite), soil cement, other rock types for road aggregate, and products from sustainably managed plantation forests instead of limestone cement. Alternative construction techniques, such as the application of pre-stressed concrete, could also help.

In and around the quarry, all environmental impacts of limestone extraction can be reduced by the fairly simple means of taking into account environmental considerations when selecting a site for exploitation. During exploitation, measures taken to reduce the impact on the surroundings will have a beneficial effect on the environment, and they will also ensure healthier conditions for the local population. After exploitation ceases, the site should not be allowed to turn into a health hazard to the local people; this can be prevented by reshaping the quarry topography. If the quarry is close to a conservation area or a town, more extensive measures could prevent a continuing negative impact of the quarry on its surroundings. These include reshaping and replanting the area. The aesthetic gains are also considerable in this case, because an abandoned quarry will not then remain a scar in the landscape.

Within a limestone area, exploitation sites should be selected so that the value of the limestone area, after extraction of the stone, is least impaired. This loss of value is the sum of lost economic value (the loss of resources other than the amount of limestone extracted from the quarry), biological value (loss of biodiversity, loss of rare environments), scientific and cultural values (religious, historical, archaeological), and aesthetic values. An area should be assessed by competent consultants in each particular field, specialists with a good reputation, good regional knowledge, and a proven ability to translate scientific information into practical recommendations for development and industrial purposes. No assumptions should be made as to the value of an area without the intervention of these consultants. An initial assessment of the expertise needed to properly assess an area should be made by a qualified generalist who, being aware of a wide range of topics related to limestone, can ensure a holistic approach to the issue, and who knows which other specialists to consult. It is particularly important that this qualified generalist is aware of biodiversity and cultural issues, fields neglected until now.

With all assessments, it is important that the methods applied and the number of person-days spent in the field are clearly stated in the report. This allows the adequacy of the assessment to be judged, and the initial findings objectively compared with subsequent monitoring results to determine the effectiveness of the mitigation measures. Suggested Elements for Consultant Terms of Reference are in the annex at the end of this report.

When assessing biodiversity, the current state of taxonomic knowledge and the scale of the problem would ideally require the engagement of a team of ecologists, conservation biologists, and specialists in various groups of animals or plants. In practice, a smaller number of broad-based specialists will typically be fielded. Assessments must not be based on informal and uncritical species lists derived from some haphazard field work, or taken at random from the often old and incomplete literature. Such procedures may easily lead to biodiversity assessments without sufficient predictive value. Next to this, the number and specialization of persons on the assessment team should reflect an a priori estimated biodiversity value of the region, its size, and the environment types present in the region.

Concerning the assessments for biodiversity, cultural property including geological features, the following are recommended:

- It should be recognized that the degraded state of a habitat does not automatically justify further conversion. The causes of its degraded state should be investigated, and its residual contribution to the environmental health of its wider surroundings should be assessed.

- It should be recognized that all natural habitats, forests, grasslands, wetlands, and water bodies alike may have a high biodiversity value, as well as a high ecological and cultural significance to the entire region.

- Biodiversity assessments should address not only the project site and its immediate surroundings, but also the wider region in which the project is located. This is necessary to properly identify hotspots of biodiversity, estimate levels of endemism, and identify individual endemic species. Also, impacts resulting from development projects often extend far beyond the border of the project site.

- An overall biodiversity analysis should not be based on a single group of organisms. Instead, in the context of limestone-related projects, special attention should be given to groups known to be important, highly diverse, or highly range restricted: higher plants, cave organisms, and snails.

Selecting Sites for Exploitation

Assuming that it has been determined that no alternative materials can be obtained, such as granite for road aggregate, preliminary suggestions to aid in the selection of sites are:

- A site for exploitation should preferably be located in limestone deposits that have already been influenced in some way. Limestone hills with a badly depleted vegetation cover, or with polluted cave systems, are to be preferred to limestone hills that are still in a pristine or near pristine state.

- Wherever possible, dolomitic limestones should be exploited instead of high-calcium limestone. The biodiversity value of dolomitic limestones is often considerably less than that of high-calcium limestones. The fact that dolomitic limestones may not meet the quality criteria for specific industries is recognized.

- An exploitation site should preferably be located in the largest limestone areas for reasons given below. The site should never extend over the entire area, but always leave a substantial part of it untouched. In large limestone areas, species may well occur that are endemic to the area as a whole, but species endemic to just a small part of it are unlikely. A well-contained and well-managed quarry in a part of a large limestone area is least likely to lead to the extinction of species.

- Selection of isolated limestone hills (that is, remote from other limestone hills) should be avoided. *The most isolated limestone hills tend to host the largest numbers of site-endemic species.* Exploiting such a hill, even when the actual quarry is relatively small, can result in a disproportionate loss of site-endemic species.

- A large quarry in one part of a large area is to be preferred above exploitation of a number of small quarries throughout the area. The latter course makes controlling the impact of the quarries on their surroundings virtually impossible.

- Sites with numerous caves should be avoided. Cave systems have a high priority for conservation because they often host unique fauna (such as bats, arthropods, or fish) that include species endemic to only a single cave system, and because they are economically important (guano, bat and swiftlet colonies for controlling pests, bat colonies for pollination and seed dispersal, bird's nests).

- Limestone bodies riddled with small voids (millimeters to centimeters wide) should be avoided because, for much of the cave fauna, small voids are more important as a habitat than large caves.

- Sites in areas with underground streams and springs should be avoided. If a quarry intersects underground water courses, there will be a disruption of the drainage system and adverse effectson the quarry itself. In addition, a quarry draining into an underground drainage system may contaminate underground water resources or drinking water far from the site.

Best Practice

The World Bank's March 1999 Operational Policy 4.01 on Environmental Assessment indicates that attention should to be given to an area that can be considerably larger than the project site alone. Thus the "area of influence" may be "the watershed within which the watershed is located, any affected estuary and coastal zone, off-site areas required for resettlement or compensatory tracts, airshed, migratory routs of humans and animals, and areas used for livelihood activities or religious or ceremonial purposes of a customary nature." In terms of the need to assess impacts of a quarry used as a source of cement in a major infrastructure project or of aggregate in a major road project, the requirement that impacts of "ancillary" aspects be addressed would apply.

In terms of Operational Policy 4.04 on Natural Habitats, it is clear that, wherever feasible, World Bank projects will be sited on lands already converted (excluding any lands that in the Bank's opinion were converted in anticipation of the project). If the EA indicates after the required "comprehensive analysis" that a project would in fact significantly convert or degrade natural habitats, the project would have to include mitigation measures acceptable to the Bank. Such measures could include, as appropriate, minimizing habitat loss (such as strategic habitat retention and postdevelopment restoration) and establishing and maintaining an ecologically similar protected area.

A New Approach Adopted

During the preparation for an investment by the International Finance Corporation[7] (IFC) in Morning Star Cement's plant in southern Vietnam, an Environmental Impact Assessment was prepared that focused on the plant operations and their impact on the immediate marine and coastal terrestrial environment. It did not review the biodiversity of the limestone hills in any detail. Since the time of that assessment there has been increasing scientific recognition of the special biological characteristics of limestone areas. Although the environmental review of the Morning Star Cement operation was generally carried out according to the standards commonly applied at the time, it was considered prudent to revisit the question of the biodiversity of these limestone hills to determine if additional management interventions are needed in this particular case, and to examine how the IFC and potential future sponsors should address these issues more generally. A study of the limestone resources in southwestern Vietnam is planned to delineate their potential uses for limestone production, biodiversity conservation, forestry production (timber and nontimber), tourism, groundwater recharge, and so forth. One focus is likely to be the overall biodiversity status of these hills, but this will be carried out in the context of the overall review of how these resources should be managed in an integrated fashion.

Responsibilities and Financing

OP4.01 makes it clear that the borrower is responsible for carrying out the environmental assessment, and that this work is to be carried out by experts not affiliated with the project. The Bank will advise the borrower on the Bank's EA requirements and review the work to determine whether the findings and recommendations provide an adequate basis for processing the project for Bank financing. When the borrower has completed or partially completed EA work before the Bank's involvement in a project, the Bank reviews the EA to ensure its consistency with the policy. If necessary the Bank may require additional work of the EA.

One simple means of financing the necessary work on limestone biodiversity and cultural heritage at a national level would be to impose a small levy on each unit of cement produced. Over a limited period, this could finance the regional resource assessments suggested in the next chapter. Another source of financing could be obtained through the Clean Development Mechanism of the Kyoto Protocol.

The Clean Development Mechanism: Implications for Cement Production

The Clean Development Mechanism (CDM) is defined by Article 12 of the Kyoto Protocol as a proposed new mechanism for pollution trading between developed (or Annex I) and developing countries. The objectives of CDM are to assist countries not included in Annex I in achieving their national sustainable development objectives, assist Annex I countries in achieving compliance with their quantified emission limitation and reduction commitments, and work toward global reductions in carbon dioxide emissions. The mechanism is still under negotiation and subject to change.

The basis of CDM is that Annex I countries have access to the technology and financial capacity to reduce carbon dioxide emissions and may have already done so. It is more efficient, however, to achieve emissions reductions in situations where emission controls are lacking, such as in non–Annex I countries—thus, the interest in pollution trading. Efficiency can be progressively increased, but each unit of improvement becomes more expensive. With limited resources, it is thus beneficial to the global atmospheric load of carbon dioxide to reduce emissions where controls can be improved cheaply. The reduction in emissions will be rewarded with credits. CDM will go into effect in the year 2000 and will continue through 2008, after which the Certified Emission Reduction (CER) credits revert to the host country.

Non–Annex I countries argue that they lack the financial capacity to make investments in pollution control technologies and that the Annex I countries did not impose pollution controls on their own industries until very recently. Why, then, should developing countries impose controls that would make their own emerging industries less competitive? Pollution trading provides a mechanism to pay for pollution control and achieve carbon dioxide emission reductions sooner than would otherwise be possible. The potential cost of reducing carbon dioxide emissions in non–Annex I countries is US$5 to $10 per ton, while carbon dioxide CERs have traded in the United States for $20 to $30 a ton. Under the Dutch Joint Implementation (JI) program, their target price is less than $10 a ton. Thus, the financial incentives exist for CDM to work. A key factor in determining CERs is that the CER must be additive. If an investment is financially viable and would have occurred anyway, it is not eligible for CERs. The project sponsor must establish a baseline, and credit is given only for reductions from that. Thus, projects must demonstrate overall reductions from existing conditions; introduction of new cleaner technology is not sufficient, as this may only add to total national carbon dioxide emissions.

There are four key players involved in any CDM deal:

- the host country government, which benefits by attracting direct foreign investments while reducing national carbon dioxide emissions
- the host country project sponsor, which benefits by receiving new technology

(Continued on next page)

- the Annex I private sector company, which invests in the project and provides technology to their host country partner and benefits by sale of technology

- the Annex I government, which applies CERs to its Kyoto commitments for carbon dioxide reductions.

Others involved include an international body to register greenhouse gas (GHG) emission reductions, public and private organizations that audit CERs, and public or private offset brokers.

CDM is relevant to the cement manufacturing sector because, although its greatest focus will be on energy efficiency, in the industrial sector, cement production is a major contributor of carbon dioxide emissions. The chemical equation for the first part of the production of cement is:

$$CaCO_3 + \text{Heat} \rightarrow CaO + CO_2.$$

Carbon dioxide is a direct waste product of both the wet and dry cement processes. Most cement plants use coal to generate heat, from which further carbon dioxide is generated. In the dry cement process, for each ton of cement produced, 0.64 ton of carbon dioxide will be emitted—0.34 from the conversion of limestone to calcium oxide, and 0.30 from the burning coal. The wet process requires approximately twice as much energy, essentially doubling coal-related carbon dioxide emissions. Thus, under CDM, a new dry-process plant producing 1 million tons of cement, which replaced an existing wet-process plant of the same capacity, would be eligible for credits equivalent to 300,000 tons of carbon dioxide saved that, via pollution trading at $10 per ton over, for example, the last five years of the CDM period, would be worth $15 million.

In periods of high economic growth, new plants would be built to meet demand and thus not count against CDM. However, most countries in East Asia are in the grip of an economic crisis, and the cement industry in particular is in a period of consolidation. CDM, and the potential financial benefits resulting from pollution trading, offer an opportunity for modernization during this period of consolidation. With appropriate influence applied, a small portion of the financial gains could be applied against national limestone resource surveys, including biodiversity and cultural property, to permit rational and least-impact exploitation to proceed when the economy becomes re-enlivened.

above. **A large cave in northern Sumatra in the concession of a cement company. The cave no longer exists.** (photo by Tony Whitten)

below. **Small-scale limestone industries for lime or local road-building material can destroy valuable habitat. In this area there used to be a colony of durian-pollinating fruit bats.** (photo by Tony Whitten)

Sharp limestone rocks on the top of a hill in Aceh, Sumatra, with a large cycad, a type of plant avidly sought for urban gardens. (photo by Tony Whitten)

A stream of wrinkle-lipped bats leaving Chao Ram Cave, northern Thailand. Throughout the region this bat lives in colonies of millions of individuals that devour tons of insects each night within a radius of 30 kilometers of the cave. These bats also produce commercial quantities of guano used as fertilizer. (photo by Dean Smart)

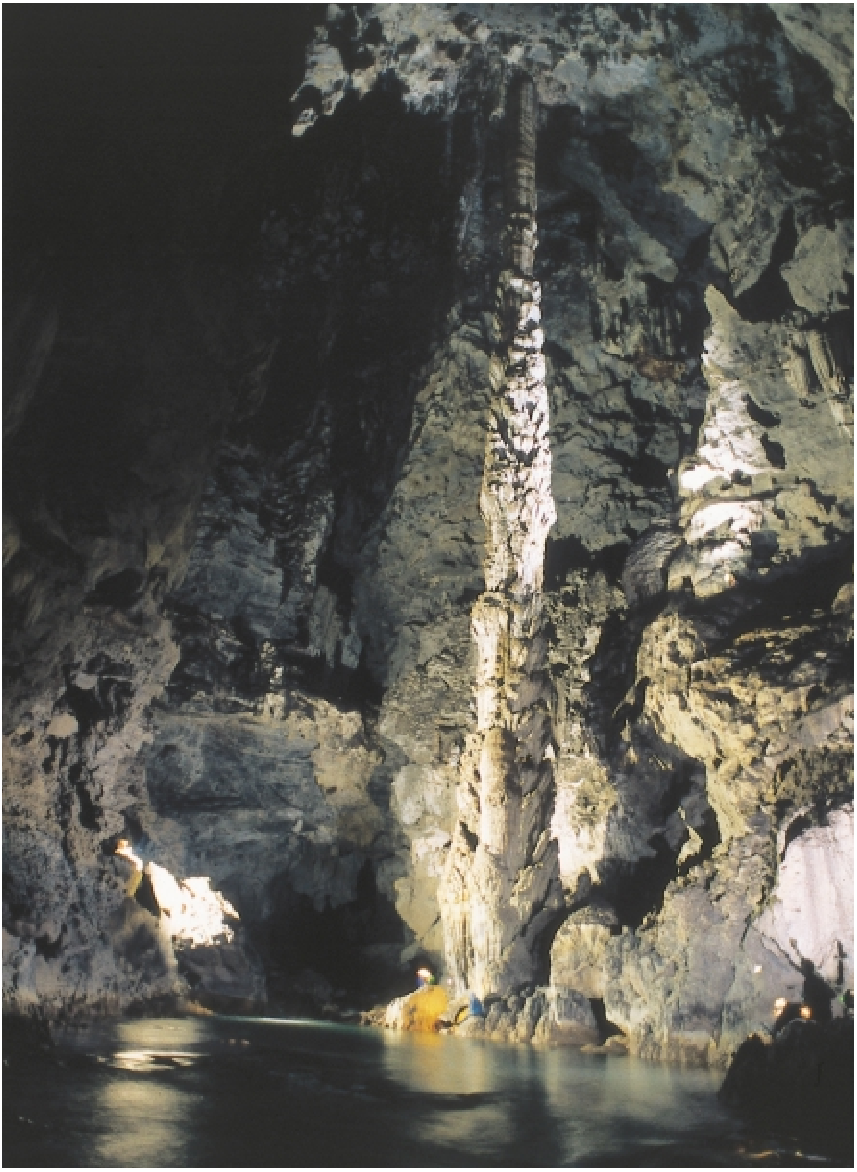
The dramatic slipper orchid *Paphiopedilum sanderianum*, with petals reaching 1 meter in length, is known from a single population in Sarawak. Although theft of plants cannot always be avoided, the species is relatively safe. (photo by Philip Cribb, Royal Botanical Gardens, Kew)

The pitcher plant *Nepenthes northiana* is one of the many animal and plant species restricted to a small range of limestone hills south of Kuching, Sarawak. (photo by A. Vogel, Leiden Botanic Gardens)

above. **Stalactites and other speleothems add beauty and aesthetic interest to a cave and also provide paleo-environmental data. These stalactites in Nam Tok Cave, western Thailand, are growing from a roof made of cemented pebbles and sediment which used to be the cave floor.** (photo by Dean Smart)

below. “**James Bond Island,” near Phangnga, southern Thailand, is visited by about 2 million tourists every year.** (photo by Dean Smart)

Cryptotora thamicola **is arguably the most specialized cave fish in the world: it has no eyes, no pigment, and seems to breathe through its skin. It lives on waterfalls in just two caves in northwest Thailand where it moves over wet rocks more like a lizard than a fish.** (photo by Dean Smart)



The tallest column in the world, 61.5 meters tall in Sao Hin Cave, western Thailand. Note the figure in the blue coat for scale. (photo by Dean Smart)

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Impact Mitigation

As was explained in the last chapter, there are considerable benefits to be gained from relatively few changes in existing working methods. National environmental agencies, donors, and companies are encouraged to develop protocols by which steps are developed and adopted to further each country's commitment to sustainable development.

The Production Phase

Quarry operation will profoundly affect the surrounding biodiversity. This can hardly be avoided, but the measures below aim to mitigate the impacts:

- Destruction of the vegetation cover and fauna: Care should be taken that the vegetation and fauna around a limestone quarry are left untouched as much as possible. The impact of the exploitation of a quarry on its surroundings includes, for example, illegal quarrying, fire, uncontrolled collecting of fuelwood, and hunting.

- Chemical pollution: Pollutants such as dust, silt, oil, fuel, and other chemicals have adverse effects on the wider surroundings of the quarrying site, both on land and in water, aboveground as well as underground. Preventive measures are necessary to avoid pollution.

- Biological pollution: The importation or escape of invasive nonnative species should be minimized through quarantine, education, and active management programs.

- Blasting: Damage to the surroundings by blasting should be minimized. Sequential blasting techniques should be applied to reduce shock waves. If bat or swiftlet colonies are present, blasting should be interrupted at the times when the animals fly out to feed or return to their roost. Also, blasting should not take place at the entrance of caves, or in a position so that the sound is directed at the opening of the cave. Blocking of cave passages, however, to protect the inside environment, should be only temporary, because long-term blocking could result in serious changes in the cave environment. Not only are the animals that regularly enter and leave affected, but also the air flow, temperature, and humidity may change, which will affect all other cave fauna.

- Erosion: Erosion resulting from road construction and other construction activities should be minimized. Cleared areas increase and concentrate the runoff. It should be ensured that rainwater can soak into the ground slowly. This can be done, for example, by using large rock chips for road metal. The draining of muddy runoff into dolines should be avoided.

- Unexpected underground water courses: If underground streams are found in a quarry close to a conservation area, the streams should be left intact.

- Chance finds of archaeological and geological remains: When archaeologically or geologically important sites (for instance, rich fossil-bearing layers) are discovered in a quarry during the course of mining, these should not be disturbed until they have been inspected by a geologist or an archaeologist. Until then, they are best covered with tough plastic sheeting overlaid with a thick layer of soil mixed with limestone talus, to protect them from erosion as well as illegal excavation. After a first inspection, a choice should be made. On less important sites, the appropriate specialists can perform an emergency excavation to sample the site and safeguard the information for the future (see below). In the event that a site turns out to be of crucial importance, it should be protected and spared by agreement between the company responsible for the exploitation of the site and the national authority responsible for archaeological or geological research and the conservation of cultural monuments. This body should be able to offer compensation to the site owner or operator for the loss of income. Without compensation, there will be no incentive for the site operator and workers to preserve archaeological and geological remains and every incentive to destroy them without notification.

The actual amount of habitat disturbance and the effects of mitigating measures should be monitored regularly, for example, at three-year intervals. This can be done by the company responsible for the exploitation.

However, to maintain objectivity and avoid conflict of interest, it is advisable to bring in independent consultants periodically for a thorough evaluation. The company responsible for the exploitation should be obliged to address recommendations following independent evaluation. If this shows serious delays or drawbacks in the monitoring and mitigation activities, the project should correct these before proceeding with the operation as scheduled.

Figure 23. Limestone hill being exploited in northern Vietnam. (photo by Tony Whitten)

Emergency Collecting and Ex Situ Conservation

If the destruction of important biodiversity or archaeological sites is inevitable even after a careful search for alternative sites, steps should be taken to safeguard relevant information about those sites for the future. A team of appropriate consultants should have opportunity to sample the biodiversity of the site, if only for a limited number of animal or plant groups. The samples should be stored and the results published. A team of archaeologists and related specialists appropriate for the situation should have an opportunity to perform emergency excavations. The site should be described and sampled, and the findings published in reputable and accessible journals.

In some cases, ex situ conservation of threatened species can be considered. Many herbaceous limestone plants, for example, have horticultural potential because of their variegated leaves, beautiful flowers, or bizarre plant shape. Besides, they are often relatively easy to cultivate and propagate, provided they are grown in a free-draining substrate, and those growing on cliffs and summits are adapted to full sun and periodic drought. Ex situ conservation of plant species could be combined with propagation for sale as garden or pot plants.

Attempts to lure colonies of bats and swiftlets in artificially made roosting places have been successful on several occasions. For example, old, disused underground mines have been made suitable for habitation by bats. In Indonesia, swiftlet colonies are housed and successfully exploited, in purpose-built houses.

If ex situ conservation experiments are undertaken, the companies involved could benefit by publicizing them to improve their public relations.

Reconstructing the Landscape

Much can be done in reconstructing limestone landscapes. Disused quarries may develop into a hazard for visitors and the local population because of collapsing rock faces, or because of stagnant pools in which the vectors of various diseases to humans and livestock may flourish. To reduce these risks wherever necessary, a terminal blast before abandoning the quarry should be part of each project. A more comprehensive reconstruction of a quarried site can be desirable when the quarry is close to a town or conservation area, to reduce the negative impact on the surroundings and for aesthetic reasons. Quarries tend to leave unsightly cavities in karst slopes, often spoiling otherwise pristine-looking tropical karst landscapes. The damage may remain visible for centuries, because the morphology of quarries is often such that colonization by plants and animals is difficult. Measures can be taken so that an abandoned quarry blends again with the surrounding natural landscape. Its faces can be remodeled to replicate the surrounding landscape, and colonization by flora and fauna can be facilitated by planting trees. Means to achieving these goals include:

- Removal of wreckage, buildings, engines, and so forth.

- Remodeling perpendicular slopes: Natural perpendicular rock faces in, for example, tower karst are formed by slow-working processes, such as undercutting by a river. Clefts and pores are usually well cemented by penetrating water, leaving behind a stable surface. Perpendicular rock faces in quarries tend to be unstable because of previous blasting, mechanical removal of rock, and the development of unloading cracks parallel to the quarry face. They may collapse and are potentially dangerous to people, and they remain visible for a long time because they are very dry, being well sheltered from rainfall.

When abandoning a quarry, it is advisable not to leave behind any near-perpendicular or overhanging rock faces and remove unstable parts. If the quarry face runs parallel to steep natural bedding in the rock, a gentler slope may be reconstructed, cutting obliquely through this bedding, to minimize the risk of rock slides along these bedding planes. Rock faces can also be terraced or otherwise be provided with notches to facilitate the establishment of vegetation. Gentle, at least nonperpendicular, slopes also enable natural karst processes that will further stabilize the slope to set in again, such as case hardening of the surface. A technique for landscaping abandoned quarries is *restoration blasting*, a set of drilling and blasting designs developed to replace a quarry face by a reconstructed landscape with rock faces, talus slopes, and buttresses similar to natural ones. This technique has been applied in karst only under temperate climates, but after a study of the morphology of locally occurring tropical karst landscapes, they can undoubtedly be applied in the tropics as well. In some cases, however, reclaiming a quarry may not be desirable at all. For example, a sawn face of a disused marble quarry may expose an outstanding example of fossil karst that is best preserved as a geological monument.

- Loosening the quarry floor: The use of heavy machinery during the production phase often compresses and hardens the soil on the quarry floor and on roads giving access to the quarry. Blasting, deep ripping, and mixing soil into fine talus will loosen the soil again and facilitate the establishment of plants.

- Ensuring sufficient draining of the quarry floor: Quarry floors often form depressions that fill with rainwater. Such ponds can constitute a health hazard because they may be a source of malaria and other parasitic diseases. A concave quarry floor should be filled in or draining ditches should be made through the lip separating the quarry floor from the surrounding land. These draining ditches should be constructed so that maintenance is necessary only during the first few years after construction. To avoid erosion by large amounts of water passing through at high speed, a reduced dip and a meandering course are preferred to concrete lining.

- Filling in crevices and holes of reconstructed gentle slopes with sterilized soil: This soil should be mixed with seeds of native species collected from nearby areas. This will stimulate the development of a vegetation cover. Once a vegetation cover is established to the extent that site-endemic plants return, the maintenance of a soil cover is no longer a goal to pursue because many of them, along with their associated animals, grow on rock surfaces or in crevices. Before opening a quarry in temperate areas, the topsoil is sometimes removed and stored carefully, to be spread out again over the quarried site after abandoning it. Dormant seeds in the soil may then help the recovery of the vegetation. In tropical countries, this technique is generally of no use because the seeds of the primary vegetation species have little or no dormancy. Limestone species appear to be an exception to this as part of their response to drought. This is an area that deserves research.

- Replanting the area: After reconstruction, it is very important that the site is covered with vegetation as soon as possible to reduce further erosion, particularly if the bedrock is fine-grained and loose. Replanting or sowing can speed up this process. To facilitate the regeneration of this pioneer vegetation cover toward the vegetation type surrounding the quarry, fast-growing woody species occurring locally in secondary vegetation probably offer the best success and are most likely to create the proper environment for recolonization by species from less disturbed vegetation surrounding the quarry. If soil conditions are appropriate, it may be possible to directly plant or encourage species of the more mature vegetation. Nonnative species should not be used. The use of artificial fertilizers and pesticides should be avoided when replanting these areas, because it can lead to pollution of underground water bodies. Many species that are suitable for replanting produce a relatively large amount of leaf litter, which increases the risk of bushfires during drought periods. It should be understood that planted forests as such have limited value as a habitat for local biodiversity and are not an effective substitute for primary or near-primary vegetation.

- Checking the results, monitoring regeneration: The reconstruction work should be financed by the company responsible for the exploitation of the site. Local or national authorities should not only check the results of the reconstruction immediately after its completion, but also at intervals of a few years. Failure to landscape a quarrying site, or failure to maintain the site afterward, should have punitive consequences for the company involved. Of course, a company cannot be held responsible for natural or man-made disasters affecting the whole area in which the quarry is situated. It is particularly important that a regime of regular firing of the vegetation is avoided, so that secondary growth can develop to maturity.

In some cases, reclaimed quarries can be put to good use again. For example, they can be converted into town parks or can be exploited as fish ponds. In Thailand, there are plans to convert limestone quarries into water reservoirs. A limestone quarry in Africa has been successfully converted into a crocodile farm and, as a spinoff, a major tourist attraction. However, the use of quarries as waste dumps should be discouraged because of the risk of groundwater pollution.

Generally, limestone areas that have been mined according to the conditions outlined in this chapter should be safeguarded against further limestone exploitation, but if renewed exploitation is proposed, a new impact assessment is required.

11

Options for the National Management of Limestone Resources

Countries are increasingly evaluating the exploitation of resources such as hydropower potential for their environmental and social as well as their economic costs and benefits. This same rational approach should be used for limestone resources to ensure that choices among candidate sites are made in a strategic and fully informed manner. Countries with limestone deposits should make systematic inventories of these deposits and collect data on their characteristics. This should include biodiversity aspects, and specialists in this field could play an important role here. National databases using geographic information system and other information software should be developed to facilitate the timely retrieval of the information.

Legislation with respect to mining operations is an important part of the process. To ensure ecological and socioeconomic soundness, in accordance with the Convention on Biological Diversity, legal conditions should be formulated and implemented to which any limestone mining operation should answer before, during, and after the actual operation. These legal conditions should include a management plan for operation, a socioeconomic impact plan, an environmental impact assessment that includes adequate attention to biodiversity, and the provision that the mining operation should minimize the pollution of air, water, and soil. These reports should be published early enough for all stakeholders to take notice and to act if necessary.

Legislative protection of species and specific ecological communities can be problematical. In some cases, limestone species, and in particular cave species, have been listed as protected species, although only one is known from East Asia (a cave fish from Central Java, Indonesia). However, the effectiveness of this approach is questionable because:

- Species must be individually identified in the legislation. This may be difficult because many species are still without a scientific name, and so cannot be listed.

- Enforcement of the law is very difficult.

- The range of such legislation is difficult to estimate without knowing the range of the protected species.

Yet legislative protection of a well-chosen keystone species could in some cases offer protection to entire communities.

The protection and management of karst areas on sites indicated in the national or other reviews should be implemented. A protected status for an area can be obtained in various ways, ranging from declaring it a national park to local authorities or companies agreeing covenants with the landowners. The following points are important in this respect:

- A protected status alone for a conservation area is not enough. It must always be accompanied by adequate resources for defined and agreed management activities. If not, increased pressure from visitors, combined with pressure from the local population, may degrade the environment.

- Wherever possible, local people should be involved in the boundary delimitation and management of the reserve, their cultural connections with the site documented and used, and their support sought through conservation education.

- Developments outside the conservation area boundaries may lead to significant changes in the water regime in the conservation area itself. This could be solved if the total watershed area is included within the conservation area boundaries, but this is not realistic in most cases. Problems could be solved by negotiations with neighboring land management agencies or landowners.

- Limestone hills assigned as conservation areas should include as wide a perimeter of forest as possible because the forest at the foot of limestone hills is richest in species. A second perimeter, comprising primary, secondary, and plantation forests, acts as a buffer between the human population and the conservation area, and serves as domestic forest to supply the needs of the local people.

- Often, perimeters of conservation areas can be combined with other land uses; near towns, for example, the second perimeter described above could act as a town’s park, with the conservation area in its center.

- International nongovernmental agencies can provide a valuable resource in supporting the declaration and strengthening the management of conservation areas. International treaties provide a further tool for the protection of conservation areas, for example, the recognition of major underground water bodies in karst areas as wetlands under the Ramsar Convention.

Endnotes

1. The term *biodiversity* (biological diversity) refers to the total variation of all forms of life on three levels—genes, species, and ecosystems—either globally or in a specified area. Disciplines within biology aim to describe various aspects of biodiversity. A taxonomist, for example, may characterize biodiversity by naming, describing, and hierarchically classifying species, but an ecologist may describe interactions between species, individuals classified according to adaptive features, and the environment within a given area.

2. Self-supporting cave systems, with no input from outside known. In such systems, all nutrients are provided by sulphur-fixing bacteria.

3. Dolomitic limestones, in which part of the calcium has been replaced by magnesium, often have less value for biodiversity conservation than high-calcium limestones.

4. Insufficient collecting undoubtedly caused their late discovery. Shells of cave molluscs may have already been collected with soil samples, but have remained unrecognized because they were not found alive and in situ.

5. It is believed that not all the bats leave the roost every night.

6. Some secondary habitats can have high numbers of species, but this is a result of mixing generally widespread species typical of disturbed areas with the species of the primary habitat.

7. IFC is the part of the World Bank Group that provides loans to the private sector.

Bibliography

Ali, S. 1957. “Edible-Nest Swiftlets in Burma.” *Journal of the Bombay Natural History Society* 54:945–46.

Amy, S. M. L., and D. S. Melville. 1994. *International Trade in Swiftlet Nests with Special Reference to Hong Kong*. Cambridge: TRAFFIC International.

Anderson, D. D. 1997. “Cave Archaeology in Southeast Asia.” *Geoarchaeology* 12:607–38.

Baillie, J., and B. Groombridge. 1996. *1996 IUCN Red List of Threatened Animals*. Gland, Switzerland: IUCN.

Banister, K. E. 1984. “A Subterranean Population of *Garra bareimiae* (Teleostei: Cyprinidae) from Oman, with Comments on the Concept of Regressive Evolution.” *Journal of Natural History* 18:927–38.

Bellwood, P. 1978. “Archaeological Research in Minahasa and the Talaud Islands, Northeastern Indonesia.” *Asian Perspectives* 19:47–69.

———. 1988. *Archaeological Research in South-Eastern Sabah*. Kota Kinabalu, Malaysia: Sabah Museum.

———. 1989. “Archaeological Investigations at Bukit Tengkorak and Segarong, Southeastern Sabah.” *Bulletin of the Indo-Pacific Prehistory Association* 9:122–62.

———. 1997. *Prehistory of the Indo-Malaysian Archipelago*. 2d ed. Honolulu: University of Hawaii Press.

Benthem Jutting, W. S. S. van. 1950. "The Malayan Species of *Boysidia, Paraboysidia, Hypselostoma* and *Gyliotrachela* (Gastropoda, Pulmonata, Vertiginidae), with a Catalogue of All the Species Hitherto Described." *Bulletin of the Raffles Museum, Singapore* 21:5–47.

———. 1952. "The Malayan Species of *Opisthostoma* (Gastropoda, Prosobranchia, Cyclophoridae), with a Catalogue of All the Species Hitherto Described." *Bulletin of the Raffles Museum, Singapore* 24:5–62.

———. 1961. "The Malayan Streptaxidae, Genera *Huttonella* and *Sinoennea*." *Bulletin of the Raffles Museum, Singapore* 26:5–33.

Bergmans, W., and F. G. Rozendaal. 1988. "Notes on Collections of Fruit Bats from Sulawesi and Some Off-Lying Islands (Mammalia, Megachiroptera)." *Zoologische Verhandelingen* 248:1–74.

Bigelow, J. 1998. "Biomes: the Promise of Cave-Dwelling Microbes." *NSS News* 56:145–53.

Boeadi, Amir, and A. Suyanto. 1983. "An Insectivorous Bat, *Tadarida plicata* (Buchanan) (Microchiroptera: Molossidae), as a Possible Component in Biological Control of Insect Pests." *Biotrop Special Publication* 18:245–47.

Boynton, R. S. 1980. *Chemistry and Technology of Lime and Limestone*. New York: John Wiley & Sons.

Brandt, R. A. M., and Temcharoen, P. 1971. "The Molluscan Fauna of the Mekong as the Foci of Schistosomiasis in South Laos and Cambodia." *Archives Mollusca* 101:111–40.

Bronson, B., and T. Asmar. 1976. "Prehistoric Investigations at Tianko Panjang Cave, Sumatra." *Asian Perspectives* 18:128–45.

Brooke, R. K. 1970. "Taxonomic and Evolutionary Notes on the Subfamilies, Tribes, Genera and Subgenera of the Swifts (Aves: Apodidae)." *Durban Museum Novitates* 9:13–24.

—. 1972. "Generic Limits in Old World Apodidae and Hirundinidae." *Bulletin of the British Ornithological Club* 92:53–57.

Bullock, J. A. 1965. “The Ecology of Malaysian Caves (and a Note on the Faunistic List from Batu Caves).” *Malayan Nature Journal* 19:57–64.

Chantler, P., and G. Driessens. 1995. *Swifts, a Guide to the Swifts and Treeswifts of the World.* Horsham, U.K.: Pica Press.

Chapman, P. 1982. “The Ecology of Caves in the Gunung Mulu National Park, Sarawak.” *Transactions of the British Cave Research Association* 9:142–62.

———. 1983. “Species Diversity in a Tropical Cave Ecosystem.” *Proceedings of the University of Bristol Speleological Society* 16:201–13.

Chu, X.-L., and Y.-R. Chen. 1979. “A New Blind Cobitid Fish from Subterranean Waters in Yunnan, China. *Acta Zoologica Sinica* 25:285–87.

Chen, Y.-R., and J. Yang. 1993a. “A Synopsis of Cavefishes from China.” *Proceedings of the XI International Congress of Speleology, August 2–8, 1993, Beijing,* pp. 121–22.

Chen, Y.-R., X.-L. Chu, Z.-Y. Luo, and J.-Y. Wu. 1988. “A New Blind Cyprinid Fish from Yunnan, China, with a Reference to the Evolution of Its Characters.” (In Chinese, summary in English.) *Acta Zoologica Sinica* 34:64–70.

———. 1993b. “Species and Origin of Cave-Dwelling *Sinocyclocheilus* fishes.” *Proceedings of the XI International Congress of Speleology, August 2–8, 1993, Beijing,* pp. 123–24.

Chen, Y.-R., J.-X. Yang, and Z.-G. Zhu. 1994. “A New Fish of the Genus *Sinocyclocheilus* from Yunnan, with Comments on Its Characteristic Adaptation (Cypriniformes: Cyprinidae).” (In Chinese, summary in English.) *Acta Zoologica Sinica* 19:246–53.

Corpuz, L. B., and J. L. Leon. 1996. “Harvesting of Edible Nests and National Policies Governing Edible Nest Swiftlets in the Philippines.” *Proceedings of the Technical Workshop on Conservation, Priority Actions, Sustainable Harvesting and Trade in Nest of Swiftlets of Collocalia in the Bird-Nest Trade, Surabaya, 4–7 November 1996.* Jakarta: CITES Secretariat / Directorate-General of Nature Conservation and Forest Protection.

Cousins, S. H. 1980. "Species Size Distribution of Birds and Snails in an Urban Area." In R. Borkham (ed.), *Urban Ecology*, pp. 117–25. Oxford: Blackwells.

Cranbrook, Earl of. 1984. "Report on the Birds' Nest Industry in the Baram District and at Niah, Sarawak." *Sarawak Museum Journal* 33:145–70.

Cranbrook, Earl of, S. Somadikarta, and S. N. Kartikasari. 1996. "Swiftlets (Aves, Apodidae, 'Collocaliini'): An Annotated Bibliography Prepared for the Department of the Environment." Paper presented at the Workshop on the Conservation of the Edible Birdnest of the Genus *Collocalia*, November 4–7, 1996. Surabaya, Indonesia.

Cribb, P. 1998. *The Genus Paphiopedilum*. 2d ed. Kota Kinabalu, Malaysia: Natural History Publications.

Dance, S. P. 1970. "Non-marine Molluscs of Borneo. I. Streptaxacea: Streptaxidae." *Journal of Conchology, London* 27:149–62.

Daoxian, Yuan. 1993. "Environmental Change and Human Impact on Karst in Southern China." *Catena Supplement* 25:99–107.

Davis, S. D., V. H. Heywood, and A. C. Hamilton. 1995. *Centres of Plant Diversity 2: Asia, Australasia and the Pacific*. Cambridge: IUCN Publications.

Davison, G. W. H. (n.d.). "Provisional Checklist of the Non-marine Molluscs of Peninsular Malaysia." Worldwide Fund for Nature Malaysia, Unpublished report. Kuala Lumpur.

———. 1995. "The Terrestrial Molluscan Fauna of Temengor Forest Reserve, Hulu Perak, Malaysia." *Malayan Nature Journal* 48:233–48.

———. 1999. "An Overview of the Importance of Limestone Outcrops to Animal Life in Peninsular Malaysia." Paper presented at the World Bank–IUCN workshop, Bangkok.

Davison, G. W. H., and R. Kiew. 1990. *Survey of Flora and Fauna of Limestone Hills in Kelantan, with Recommendations for Conservation*. Kuala Lumpur: Worldwide Fund for Nature Malaysia.

Deharveng, L. 1987. “Cave Collembola of South-East Asia.” *Korean Journal of Systematic Zoology* 3:165–74.

———. 1989. « La Faune souterraine de Batu Lubang. » In *Expédition Batukarst 88, rapport spéléologique et scientifique*: 37-46. Toulouse, France: Association pyrénéenne de Spéléologie.

Deharveng, L., and A. Bedos. 1995. « La Faune souterraine de Sumatra Barat. » In *Expédition Sumatra 93, rapport spéléologique et scientifique*: 41-44. Toulouse: Association pyrénéenne de Spéléologie.

———. 1999 (in press). “The Cave Fauna of Southeast Asia. Origin, Evolution and Ecology.” In H. Wilkens, D. Culver, and B. Humphreys (eds.), *Ecosystems of the World. Subterranean Ecosystems*. New York: Springer-Verlag.

———. 1999 (in press). « Thaïlande. » In C. Juberthie and V. Decu (eds.), *Encyclopaedia biospeologica*. Moulis, France.

Deharveng, L., J. P. Besson, and F. Brehier. 1999 (in press). « Laos. » In C. Juberthie and V. Decu (eds.), *Encyclopaedia biospeologica*. Moulis, France.

Deharveng, L., and Le Cong Kiet. 1999 (in press). « Vietnam. » In C. Juberthie and V. Decu (eds.), *Encyclopaedia biospeologica*. Moulis, France.

Deharveng, L., and P. Leclerc. 1989. Recherches sur les faunes cavernicoles d'Asie du Sud-Est. *Mémoires de Biospéologie* 16:91–110.

Dobat, K., and T. Peikert-Holle. 1985. *Blüten und Fledermäuse*. Frankfurt am Main, Germany: Waldemar Kramer

Dunkley, John D. 1995. *The Caves of Thailand*. Sydney, Australia: Speleological Research Council.

Dunn, F. L. 1964. “Excavations at Gua Kechil, Pahang.” *Journal of the Malaysian Branch of the Royal Asiatic Society* 37:87–124.

EPC (Environmental Protection Center). 1997. *Environmental Impact Assessment of the Nghi Son Cement Corporation Project in the Socialist Republic of Vietnam, Executive Summary*. Unpublished report. Hanoi, Vietnam.

Fan, Zhiyong, and Fenqi He. 1997. “The Status and Trade of Edible-Nest Swiftlets, genus *Collocalia*, in China.” *Tigerpaper* 24:31–32.

Fox, R. B. 1970. *The Tabon Caves: Archaeological Explorations and Excavations on Palawan Island, Philippines*. Manila: National Museum Monograph 1.

Francis, C. M. 1987. *The Management of the Edible Bird’s Nest Caves in Sabah*. Sabah Forest Department, Sabah, Malaysia.

Fromaget, J. 1940. « Les Récentes Découvertes anthropologiques dans les formations préhistoriques de la chaîne Annamitique. » *Proceedings of the Third Congress of Prehistorians of the Far East, Singapore, 1938* :51–59.

Fujita, M. S., and M. D. Tuttle. 1991. “Flying Foxes (Chiroptera: Pteropodidae): Threatened Animals of Key Ecological and Economic Importance.” *Conservation Biology* 5:455–63.

Gagen, P., and J. Gunn. 1987a. “A Geomorphological Approach to Restoration Blasting in Limestone Quarries.” In B. F. Berry (ed.), *Karst Hydrogeology: Engineering and Environmental Applications*. Rotterdam: Balkema.

———. 1987b. “Restoration Blasting in Limestone Quarries.” *Explosives Engineering* 1:14–15.

Gardenfors, U. 1986. *Impact of Airborne Pollution on Terrestrial Invertebrates, with Particular Reference to Molluscs*. National Swedish Environmental Protection Board Report 3362. Stockholm.

Gaston, K. J., and E. Hudson. 1994. “Regional Patterns of Diversity and Estimates of Global Insect Species Richness.” *Biodiversity and Conservation* 3:493–500.

Gibert, J. 1987. 11. « Le Système karstique du Doi Chiang Dao (Thaïlande). Peuplements aquatiques souterrains, répartition, relations entre le milieu karstique et le sous-écoulement de l'exutoire. » In *Expédition Thaï-Maros 86, rapport spéléologique et scientifique*: 117–28. Toulouse, France: Association pyrénéenne de Spéléologie.

Glover, I. C. 1972. “Alfred Bühler's Excavations in Timor: A Re-evaluation.” *Art and Archaeology Research Papers* 2:117–42.

———. 1976. “Ulu Leang Cave, Maros: A Preliminary Sequence of Post-Pleistocene Cultural Development in South Sulawesi.” Archipel 11:113–54.

———. 1979. “The Effects of Sink Action on Archaeological Deposits in Caves: An Indonesian Example.” *World Archaeology* 10:302–17.

———. 1981. “Leang Burung 2: An Upper Palaeolithic Rockshelter in South Sulawesi, Indonesia.” *Modern Quaternary Research in Southeast Asia* 6:1–35.

———. 1986. *Archaeology in Eastern Timor, 1966-67*. Department of Prehistory, Research School of Pacific Studies, Australian National University, Canberra.

Good, L. K. 1993. “The Status of the Black Nest Swiftlets in Niah.” *Tigerpaper* 20:15–18.

Griffin, D. R. 1958. *Listening in the Dark; the Acoustic Orientation of Bats and Men*. New Haven, Conn.: Yale University Press.

Groot, R. A. de. 1983. “On the Trail of Bird’s Nest Soup: Caves, Climbs and High Stakes.” *Smithsonian* 14: 66–74.

Gunn, J. 1986. “Solute Processes and Karst Landforms.” In S. T. Trudgill (ed.), *Solute Processes*. New York: John Wiley & Sons.

———. 1993. “The Geomorphological Impacts of Limestone Quarrying.” *Catena Supplement* 25:187–97.

———. 1999. “Landscape Reconstruction after Quarrying.” Paper presented at the World Bank–IUCN workshop, Bangkok.

Gunn, J., D. Bailey, and J. Handley. 1997. *The Reclamation of Limestone Quarries Using Landform Replication*. University of Huddersfield, U.K.

Gunn, J., and P. Gagen. 1987. “Limestone Quarrying and Sinkhole Development in the English Peak District.” In B. F. Berry (ed.), *Karst Hydrogeology: Engineering and Environmental Applications*. Rotterdam: Balkema.

Ha Van Tan. 1980. Nouvelles recherches préhistoriques et protohistoriques au Vietnam. *Bulletin de l'Ecole française d'Extrême-orient* 68:113–54.

———. 1997. "The Hoabinhian and Before." *Bulletin of the Indo-Pacific Prehistory Association* 16:35–42.

Hamilton-Smith, E. 1999. "Concepts and Principles for the Protection of Karst-Related Biota." Paper presented at the World Bank–IUCN workshop, Bangkok.

Hardwick, P., and J. Gunn. 1993. "The Impact of Agriculture on Limestone Caves." *Catena Supplement* 25:235–49.

Hawes, R. S. 1939. "The Flood Factor in the Ecology of Caves." *Journal of Animal Ecology* 8:1–5.

Heekeren, H. R. van. 1957. *The Stone Age of Indonesia*. The Hague: M. Nijhoff.

Heekeren, H. R. van, and E. Knuth. 1967. *Archaeological Excavations in Thailand. Vol.1: Sai Yok*. Copenhagen: Munksgaard.

Heywood, V. H. 1995. *Global Biodiversity Assessment*. Cambridge: Cambridge University Press.

Hobbs, H. H., and M. A. Daniel. 1977. "A Review of the Troglobitic Decapod Crustaceans of the Americas." *Smithsonian Contributions to Zoology* 244:1–183.

Holthuis, L. B. 1978. "Zoological Results of the British Speleological Expedition to Papua New Guinea 1975. 7. Caernicolous Shrimps (Crustacea Decapoda, Natantia) from New Ireland and the Philippines." *Zoologische Mededelingen* 53:209–24.

———. 1984. "Freshwater Prawns (Crustacea Decapoda: Natantia) from Subterranean Waters of the Gunung Dewu Area, Central Java, Indonesia." *Zoologische Mededelingen* 58:141–48.

Holyoake. D. T. 1978. "Effects of Atmospheric Sulphur Dioxide on the Distribution of *Balea perversa* in Southern Britain." Journal of Conchology, London 29:319–23.

Howarth, F. G. 1980. “The Zoogeography of Specialized Cave Animals: A Bioclimatic Model.” *Evolution* 34:394–406.

———. 1981. “The Conservation of Cave Invertebrates.: In J. E. Mylroie (ed.), *Proceedings of the First International Cave Management Symposium, Murray Ky., July 15–18, 1981.*

———. 1982. “Bioclimatic and Geologic Factors Governing the Evolution and Distribution of Hawaiian Cave Insects.” *Entomologia Generalis* 8:17–26.

———. 1983. “Ecology of Cave Arthropods.” *Annual Review of Entomology* 28:365–89.

———. 1987. “The Evolution of Nnon-relictual Tropical Troglobites.” *International Journal of Speleology* 16:1–16.

———. 1988. “Environmental Ecology of North Queensland Caves: Or Why There Are So Many Troglobites in Australia.: In L. Pearson (ed.), *Preprints of Papers for the 17th Biennial Conference, Australian Speleological Federation Tropicon Conference, Lake Tinaroo, Far North Queensland, 27–31 Dec. 1988.* Cairns: Australian Speleological Federation.

———. 1990. “Elevated Carbon Dioxide Levels in Bayliss Cave, Australia: Implications for the Evolution of Obligate Cave Species.” *Pacific Science* 44:207–18.

———. 1991. “Hawaiian Cave Faunas: Macroevolution on Young Islands.” In E. C. Dudley (ed.), *The Unity of Evolutionary Biology*. Portland, Ore.: Dioscorides Press.

Humphreys, W. F. 1993. “Cave Fauna in Semi-Arid Tropical Western Australia: A Diverse Relict Wet Forest-Litter Fauna.” *Mémoires de Biospéléologie* 20:105–10.

Huppert, G., E. Burri, P. Forti, and A. Cigna. 1993. “Effects of Tourist Development on Caves and Karst.” *Catena Supplement* 25:251–68.

Juberthie, C., and V. Decu. 1994. *Encyclopaedia biospeleogica.* Moulis, France.

Kang, H., C. Hail, and J. Sigurdsson. 1991. “Nest Construction and Egg-Laying in the Edible-Nest Swiftlets (*Aerodramus* spp.) and the Implications for Harvesting.” *Ibis* 133:170–77.

Kang, N., and P. G. Lee. 1991. “The Edible-Nest Swiftlets *Aerodramus* spp.” *Nature Malaysiana* 16:44–51.

Kang, Y. C., W. M. Keung, T. T. Tip, K. M. Ko, S. W. Tsao, and M. H. Ng. 1987. “Evidence that Epidermal Growth Factor Is Present in Swiftlet’s (*Collocalia*) Nest.” *Comparative Biochemical Physiology* 87B:221–26.

Khang, P. 1991. « Présentation des régions karstiques du Vietnam. » *Karstologia* 18:1–12.

Kiet, Le Cong. 1970. « La Végétation des collines calcaires de la région de Kien-Luong—Ha Tien. » *Nien-San* 3:121–200.

———. 1974. « La Végétation des collines calcaires de la région de Kien-Luong—Ha Tien (suite). » *Nien-San* 4:11–90.

Kiew, R. 1991. “The Limestone Flora.” In R. Kiew (ed.), *The State of Nature Conservation in Malaysia.* Kuala Lumpur: Malayan Nature Society.

———. 1997. “The Malaysian Highlands and Limestone Hills: Threatened Ecosystems.” In *State of the Environment in Malaysia*, pp. 187–95. Consumers’ Association of Penang, Malaysia.

Kiew, R., A. Weber, and B. L. Burtt. 1997. “Three New Genera of Gesneriaceae from Limestone of Peninsular Malaysia.” *Beitrage Biologische Pflanzen* 70:383–403.

Kottelat, M. 1990. “New Species and Populations of Cave Nemacheilines in South and Southeast Asia (Osteichthyes: Balitoridae).” *Mémoires de Biospéologie* 17:49–56.

———. 1998. “*Homaloptera yuwonoi,* a New Species of Hillstream Loach fron Borneo, with a New Generic Name for *H. thamicola* (Teleostei: Balitoridae).” *Ichthyological Exploration of Freshwaters* 9:267–72.

Kottelat, M., and F. Bréhier. 1999. (in press). “*Troglocyclocheilus khammouanensis,* a New Genus and Species of Cave Fish from the Khammouan Karst, Laos (Teleostei: Cyprinidae).” *Revue Suisse de Zoologie* 105.

Kottelat, M., and J. Géry. 1989. "*Nemacheilus troglocataractus,* a New Blind Cavefish from Thailand." *Spixiana* 11:273–77.

Laidlaw, F. F. 1949. "The Malayan species of *Diplommatina* (Cyclophoridae)." *Bulletin of the Raffles Museum, Singapore* 19:199–215.

Langham, N. 1980. "Breeding Biology of the Edible-Nest Swiftlet *Aerodramus fuciphagus.*" *Ibis* 122:447–61.

Lauritzen, S.-E. 1993. "Natural Environmental Change in Karst: The Quaternary Record." *Catena Supplement* 25:21–40.

Leh, C. M. U. 1993. *A Guide to Birds' Nest Caves and Birds' Nests of Sarawak.* Kuching, Malaysia: The Sarawak Museum.

Leroy, Y. 1967. « Gryllides et gryllacrides cavernicoles. » *Annales de Spéléologie* 22:659–722.

Lindberg, K. 1960. « Revue des recherches biospéléologiques en Asie moyenne et dans le sud du continent asiatique. » *Rassegna Speleologie Italiana* 12:43–50.

MacKinnon, K., G. Hatta, H. Halim, and A. Mangalik. 1996. *The Ecology of Indonesia Series. Vol. III. The Ecology of Kalimantan (Indonesian Borneo).* Singapore: Periplus Editions.

Majid, Z. 1992. *The Excavation of "Perak Man," an Epi-palaeolithic burial Bat Gua Gunung Runtuh.* University Sains, Pinang, Malaysia.

Mangen, J.-M. 1993. "Ecology and Vegetation of Mt Trikora, New Guinea (Irian Jaya/Indonesia)." *Travaux scientifiques du Musée National d'Histoire Naturelle de Luxembourg* 21:1–216.

Matthews, J. M. 1961. *A Check-List of "Hoabinhian" Sites Excavated in Malaya, 1860–1939.* Singapore: Eastern Universities Press.

Mawdsley, N. A., S. G. Compton, and R. J. Whittaker. 1998. "Population Persistence, Pollination Mutualisms, and Figs in Fragmented Tropical Landscapes." *Conservation Biology* 12:1416–20.

McClure, H. E. 1965. "Microcosms of Batu Caves and a List of Species Collected at Batu Caves." *The Malayan Nature Journal* 19:65–74.

McClure, H. E., Liat Lim Boo, and S. E. Winn. 1967. "Fauna of the Dark Cave, Batu Caves, Kuala Lumpur, Malaysia." *Pacific Insects* 9:399–428.

Medway, Lord. 1957. "Birds' Nest Collecting." *Sarawak Museum Journal* n.s. 8:252–60.

———. 1959. "Echolocation among *Collocalia*." *Nature* 184:1352–53.

———. 1960. "Cave Swiftlets." In B. E. Smythies (ed.), *The Birds of Borneo*. Edinburgh: Oliver and Boyd.

———. 1962a. "The Relation between the Reproductive Cycle, Moult and Changes in the Sublingual Salivary Glands of the Swiftlet *Collocalia maxima* Hume." *Proceedings of the Zoological Society of London* 138:305–15.

———. 1962b. "The Swiftlets (*Collocalia*) of Niah Cave, Sarawak. Part I. Breeding Biology." *Ibis* 104:45–66.

———. 1962c. "The Swiftlets (*Collocalia*) of Niah Cave, Sarawak. Part II. Ecology and the Regulation of Breeding." *Ibis* 104:228–45.

———. 1963. "The Antiquity of Trade in Edible Birds' Nest." *Federated Museums Journal* n.s. 8:36–47.

Medway, Lord, and J. D. Pye. 1977. "Echolocation and the Systematics of Swiftlets.: In B. Stonehouse and C. Perrins (eds.), *Evolutionary Ecology*. London: Macmillan.

Mickleburgh, S. P., A. M. Hutson and P. A. Racey (compilers). 1992. *Old World Fruit Bats; an Action Plan for Their Conservation*. Gland, Switzerland: IUCN.

Momberg, F., B. Mambai, and H. van Noord. 1998. "Justification for the Nomination of Lorentz National Park as a World Heritage Site." WWF Technical Memorandum No. 2. Jakarta, Indonesia.

Monastyrskii, A. L. 1999. *Butterfly Fauna on Limestone (an Example of Ba Be National Park)*. Unpublished report. Vietnam-Russia Research Tropical Center, Hanoi, Vietnam.

Mourer, R. 1977. "Laang Spean and the Prehistory of Cambodia." *Modern Quaternary Research in Southeast Asia* 3:29–56.

Mulvaney, D. J., and R. P. Soejono. 1972. "The Australian-Indonesian Expedition to Sulawesi." *Asian Perspectives* 13:163–77.

Nadler, T. 1996. "Report on the Distribution and Status of Delacour's Langur (*Trachypithecus delacouri*)." *Asian Primates* 6:1–3.

Ng, H. H., and M. Kottelat. 1998. "*Pterocryptis buccata*, a New Species of Catfish from Western Thailand (Teleostei: Siluridae) with Epigean and Hypogean Populations." *Ichthyological Research* 45:393–99.

Ng, P. K. L., and Whitten, A. J. 1995. "On a New Cave-Dwelling *Sesarmoides* (Crustacea: Decapoda: Brachyura: Grapsidae) from Nusa Penida, Bali, Indonesia." *Tropical Biodiversity* 2:369–76.

Nguyen Quang Phach. 1994. "Breeding and Moult of the Edible-Nest Swiftlets *Collocalia fuciphaga germani* in Vietnam." *Alauda* 62:107–15.

Novick, A. 1959. "Acoustic Orientation in the Cave Swiftlet (*Collocalia brevirostris unicolor*)." *Biological Bulletin of the Marine Laboratory of Woods Hole* 117:497–503.

Oldfield, S., C. Lusty, and A. MacKinven. 1998. *The World List of Threatened Trees*. Cambridge: World Conservation Press.

Orolfo, P. 1961. "Discovery of Bird's Nest Caves in North Borneo." *Sarawak Museum Journal* 10:270–73.

Pakpahan, A. M., and T. R. Soehartono. 1994. "Current Situation of the Edible-Nest Swiftlets in Indonesia." Paper presented at the 1994 Convention of the Parties to CITES meeting in Miami, Florida.

Panha, S., and J. Burch. 1998. "Species Diversity of Micro-Snails in Thailand.: In R. Bieler and P.M. Mikkelsen (eds.), *Abstracts, World Congress of Malacology, Washington, D.C., 1998*.

Pham, H. T. 1983. "Con Moong Cave: A Noteworthy Archaeological Discovery in Vietnam." *Asian Perspectives* 23:17–22.

Pookajorn, S. 1990. "Hoabinhian Cave Excavations in Ban Kao District, West Thailand." In I. C. and E. A. Glover (eds.), *Southeast Asian Archaeology 1986*. Oxford: British Archaeological Reports.

———. 1995. "Interpretation of Archaeological Context of Late Pleistocene to Middle Holocene from Mon Khiew Cave, Krabi Province, and Sakai Cave, Trang Province." In S.-A. Khaisri (ed.), *Studies and Reflections on Asian Art History and Archaeology. Essays in Honour of H.S.H. Professor Suphadradis Diskul*. Bangkok: Silpakorn University.

Proudlove, G. S. 1997. "A Synopsis of the Hypogean Fishes." *Proceedings of the 12th International Congress of Speleology, La Chaux-de-Fonds* 3:51–56.

———. 1997. "The Conservation Status of Hypogean Fishes." *Proceedings of the 12th International Congress of Speleology, La Chaux-de-Fonds* 3:56–58.

Raharjo, Y. C., A. Hoo, S. Wiryoatmodjo, and M. Subrata. 1996. "Nest Production and Management Systems of Cave-Inhabiting *Collocalia fuciphaga* and *C. maxima* from Some Known Areas in Indonesia." In *Proceedings of the Technical Workshop on Conservation, Priority Actions, Sustainable Harvesting and Trade in Nest of Swiftlets of* Collocalia *in the Bird-Nest Trade, Surabaya, 4–7 November 1996*. Jakarta: CITES. Secretariat / Directorate-General of Nature Conservation and Forest Protection.

Romero, A. 1985. "Cave Colonization by Fish: Role of Bat Predation." *American Midland Naturalist* 113:7–12.

Samways, M. J. 1993. "Insects in Biodiversity Conservation—Some Perspectives and Directives." *Biodiversity and Conservation* 2:258–82.

Sankaran, R. 1995. *Impact Assessment of Nest Collection on the Edible-Nest Swiftlet in the Nicobar Islands*. SACON Occasional Report 1. Salim Ali Centre for Ornithology and Natural History, Bombay.

———. 1998. *The Impact of Nest Collection on the Edible-Nest Swiftlet* Collocalia fuciphaga *in the Andaman and Nicobar Islands*. Bombay: Salim Ali Centre for Ornithology and Natural History.

Sieveking, G. 1954. “Excavations at Gua Cha, Kelantan, 1954, Part 1.” *Federation Museums Journal* 1–2:75–143.

Smith, D. I. 1993. “The Nature of Karst Aquifers and Their Susceptibility to Pollution.” *Catena Supplement* 25:41–58.

Smitinand, T. 1966. “The Vegetation of Doi Chiengdao, a Limestone Massive in Chiengmai, North Thailand.” *Natural History Bulletin of the Siam Society* 21:93–128.

Sørensen, P. 1979. “The Ongbah Cave and its Fifth Drum.” In R. Smith and W. Watson (eds.), *Early South-East Asia. Essays in Archaeology and Historical Geography*. Oxford: Oxford University Press.

Suthers, R. A., and D. H. Hector. 1982. “Mechanisms for the Production of Echolocating Clicks by the Grey Swiftlet, *Collocalia spodiopygia*.” *Journal of Comparative Physiology* 148:457–70.

Taha, A. H. 1991. “Gua Cha and the Archaeology of the Orang Asli.” *Bulletin of the Indo-Pacific Prehistory Association* 11:363–72.

Thiel, B. 1990. “Excavations at Arku Cave, Northeast Luzon, Philippines.” *Asian Perspectives* 27:229–64.

Thinès, G. 1983. « Examen de quelques hypothèses sur la biologie générale et l’éthologie des poissons cavernicoles. ’ *Annales de la Société Royale Zoologique de Belgique* 113 (suppl. 1):227–38.

Thinès, G., and G. S. Proudlove. 1986. “Pisces.” In L. Botosaneanu (ed.), *Stygofauna Mundi. A Faunistic, Distributional, and Ecological Synthesis of the World Fauna Inhabiting Subterranean Waters (Including the Marine Interstitial)*. Leiden, the Netherlands: Brill.

Trajano, E. 1991. “Population Ecology of *Pimelodella kronei*, Troglobitic Catfish from Southeastern Brazil (Siluriformes, Pimelodidae).” *Environmental Biology of Fishes* 30:407–21.

———. 1997. “Food and Reproduction of *Trichomycterus itacarambiensis*, Cave Catfish from South-eastern Brazil.” *Journal of Fish Biology* 51:53–63.

Tuggle, H. D., and K. L. Hutterer. 1972. “Archaeology of the Sohoton Area, Southwestern Samar, Philippines.” *Leyte-Samar Studies* 6:1–132.

Tuttle, M. D. 1990. “Return to Thailand.” *Bats* 8:7–11.

Tuttle, M. D., and D. A. R. Taylor. 1998. *Bats and Mines*. Resource Publication 3. Austin, Texas: Bat Conservation International, Inc.

Tweedie, M. W. F. 1953. “The Stone Age in Malaya.” *Journal of the Malaysian Branch of the Royal Asiatic Society* 26:1–90.

———. 1961. “On Certain Mollusca of the Malayan Limestone Hills.” *Bulletin of the Raffles Museum, Singapore* 26:49–65.

Urushibara-Yoshino, K. 1993. “Human Impact on Karst Soils: Japanese and Other Examples.” *Catena Supplement* 25:219–33.

Verhoeven, T. 1959. » Der Klingenkultur der Insel Timor. « *Anthropos* 54:970–72.

Vermeulen, J. J. 1993. “Notes on the Non-marine Molluscs of the Island of Borneo, 5. The Genus *Diplommatina* (Gastropoda Prosobranchia: Diplommatinidae).” *Basteria* 57:3–69.

———. 1994. “Notes on the Non-marine Molluscs of the Island of Borneo, 6. The Genus *Opisthostoma* (Gastropoda Prosobranchia: Diplommatinidae), Part 2.” *Basteria* 58:73–191.

———. 1996. “Notes on the Non-marine Molluscs of the Island of Borneo, 8. The Genus *Arinia*; Additions to the Genera *Diplommatina* and *Opisthostoma* (Gastropoda Prosobranchia: Diplommatinidae).” *Basteria* 60:87–138.

Vermeulen, J. J., and A. J. Whitten. 1998. *Fauna Malesiana Guide to the Land Snails of Bali*. Leiden, the Netherlands: Backhuys Publishers and Fauna Malesiana Foundation.

Verstappen, H. Th. 1960. “Some Observations on Karst Development in the Malay Archipelago.” *Journal of Tropical Geography* 14:1–10.

———. 1964. “Karst Morphology of the Star Mountains (Central New Guinea) and Its Relation to Lithology and Climate.” *Zeitschrift für Geomorphologie* n.f. 8:40–49.

Vidal, J. 1956. « La Végétation du Laos, 1re partie: le milieu. » *Travails Laboratorie Forestrie Toulouse* 5:1–120.

———. 1960. « La Végétation du Laos, 2me partie: groupements végétaux et flore. » *Travails Laboratorie Forestrie Toulouse* 5:121–582.

Walter, K. S., and H. J. Gillett (eds.). 1998. *1997 IUCN Red List of Threatened Plants*. Gland, Switzerland, and Cambridge: IUCN.

Waltham, T. 1998. *Limestone Karst of Ha Long Bay, Vietnam*. Engineering Geology Report # 806. Trent University, Nottingham, U.K.

Watson, J., E. Hamilton-Smith, D. Gillieson, and K. Kiernan (eds.). 1997. *Guidelines for Cave and Karst Protection*. Gland, Switzerland, and Cambridge: IUCN.

Whitten, T., J. Anwar, S. J. Damanik, and N. Hisyam. 1999. *The Ecology of Indonesia Series. Vol. I. The Ecology of Sumatra*. Oxford: Oxford University Press.

Whitten, T., R. E. Soeriaatmadja, and S. Afiff. 1996. *The Ecology of Indonesia Series. Vol. II. The Ecology of Java and Bali*. Oxford: Oxford University Press.

Widmann, P. 1996. *Importance of Fruit Bats for Pollination and Seed Dispersal in Orchards and Forests in Leyte, Philippines*. Deutsche Gesellschaft für Technische Zusammenarbeit, Eschborn.

Williams, P. H., C. J. Humphries, and R. I. Vane-Wright. 1991. "Measuring Biodiversity: Taxonomic Relatedness for Conservation Priorities." *Australian Systematic Botany* 4: 665–79.

Williams, P. W. 1993. "Environmental Change and Human Impact on Karst Terrains: An Introduction." *Catena Supplement* 25:1–19.

Yang, Junxing, and Yinrui Chen. 1994. "The Cavefishes from Duan, Guangxi, China, with Comments on Their Adaptations to Cave Habitats." *Proceedings of the XI International Congress of Speleology, August 2–8, 1993, Beijing*, pp. 124–26.

———. 1994. "The Cavefishes from Jiuxiang Limestone Cave of Yunnan, China, with Reference to the Character Evolutions." *Proceedings of the XI international congress of speleology, August 2–8, 1993, Beijing*, pp. 126–28.

Zhu Hua, Wang Hong, and Li Baobui. 1998. "The Structure, Species Composition and Diversity of the Limestone Vegetation in Xishuangbanna, SW China." *Gardens' Bulletin Singapore* 50:5–30.

Annex

Suggested Elements for Consultant Terms of Reference

A biodiversity or cultural property consultant should be able to conduct an average assessment within a total period varying from 2 to 10 weeks, including 2 or more weeks of fieldwork. This largely depends on the information already available, the specialization, the infrastructure of the area, and the amount of preparation. Although a archaeologist is often able to submit a subfinal version of his or her report before or shortly after returning from fieldwork, a biodiversity consultant is rarely able to do so, particularly if he or she works on groups with numerous species. Where there is significant temporal and spatial variation in species, a biodiversity consultant may require two or more visits to the site and surrounding area to gather sufficient data for the necessary comprehensive analysis.

Biodiversity

Most biodiversity consultants combine a superficial knowledge of plants and animals in general with a deep knowledge of one or a few groups. A biodiversity consultant can be expected to perform the following:

- preparatory work to establish the temporal and spatial sampling design, taking into account the published literature and other information

- field work to sample the area under investigation and surrounding areas to an extent that the results give a good impression of the biodiversity present, without necessarily being exhaustive

- materials analysis to sort the collected samples and identify species as far as taxonomic knowledge currently available allows

- materials analysis to recognize and sample interesting species of other groups, and send these samples to appropriate specialists for identification and evaluation

- assessment report to:
  - draw up species lists for each site sampled, noting endemic species
  - identify "hotspots" for the fauna and flora
  - identify communities of species living in different habitats and describe the differences among the fauna of the sampled sites
  - identify threats to the biodiversity of the area studied
  - relate the results to general environmental, taxonomic, and biogeographical knowledge of the region
  - advise on the selection of sites suitable both for exploitation and protection
  - identify economic values of elements of the group under study as well as the fauna and flora in general
  - design a monitoring and assessment program.

Biodiversity consultants will need time (one to two months) after the fieldwork to process and identify the samples. The lists produced will form the basis for the analysis and final assessment report.

Archaeology, History, Cultural Property, and Scenic Values

The archaeological, historical, and cultural values of all the sites considered for exploitation, including the immediate surrounding area, should be assessed. The consultant can be expected to perform the following after literature searches and field work:

- produce a written introduction to the human history and contemporary culture of the area

- identify the various periods for which remnants of human presence are found within the area

- locate and evaluate sites containing remnants of human presence

- locate and evaluate sites (above- and underground) of cultural importance for the local population and on a national scale

- locate and evaluate sites of extraordinary scenic value and with current cultural meaning

- advise on the selection of the exploitation sites so that the least possible damage to archaeological, historical, and cultural sites is done.

The consultant, most likely an archaeologist, should work in cooperation with geologists and geomorphologists, and particularly in cooperation with local historians and other well-informed local people.

Geology, Geomorphology, and Hydrology

A geological, geomorphological, and hydrological consultant should:

- include a short geological description of the area under investigation, particularly referring to the limestone occurring there

- describe the various limestone deposits present in the area, and locate limestone deposits of a special nature, such as dolomitic limestone (Dolomitic limestones often have less biodiversity and archaeological value that high-calcium limestones. They cannot be used for cement, but they could be an alternative for other uses of limestone.)

- locate and describe structures and deposits within the area that contain information about the geological past, which are often of unique scientific value

- locate and describe the karst landforms present in the area, and locate rare landforms or landforms of special value (Special attention should be paid to buried karst.)

- locate and describe cave systems (If present, caves on the potential sites should be explored, sampled, and mapped by speleologists.)

- advise on the desirability of exploitation sites in the area, as well as on their least harmful location

- identify sites where limestone of the appropriate quality but with minimal karstification is available

- investigate and map the water circulation in and around a potential site, if reservoirs are present or if the limestone area plays an obvious role in the hydrological system of its surroundings.

This assessment should include aesthetic and economic components, as well as a scientific component.

Economic Values

The economic analysis typically would not include the full range of costs and benefits related to environmental and cultural matters. Perhaps as a result of the author's work with the other consultants described above, the report on economic values would include sources of income for the regional population, for example:

- reservoirs of high-quality drinking water
- fuelwood
- nontimber forest products
- bird's nests and guano
- tourist exploitation.

It would also include more general economic values, for example, for the environmental health of the region, including essential ecosystem services such as:

- watershed protection
- roosting places of bat and swiftlet colonies that pollinate fruit and timber crops, and destroy large quantities of insects infesting crops
- aesthetic and cultural values.

Aesthetic and cultural values are important in the economic analysis because, even without immediately cashing in on them through tourist exploitation, a beautiful landscape will add to the general well-being of its inhabitants in the long term. It gives people "roots" and a cultural identity: all over the world, people feel a lifelong bond with the area where they were born, and with its special features.

All these aspects should be included in an assessment of the economic values of limestone sites. The economic values to the local population are probably best assessed by an anthropologist. In fact, all consultants working in the area should address these issues and be aware of possible uses of the studied sites by the local population.