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Don't forget subterranean ecosystems in global biodiversity conservation and climate change mitigation agendas

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To the Editor—Climate change is a mounting threat to biodiversity, affecting multiple ecosystem services critical for human wellbeing, and hence, the achievement of most Sustainable Development Goals[1]. To address this herculean challenge, several global initiatives at the crossroads of science and policy have been advanced to implement bold and effective post-2020 biodiversity and climate change agendas[2]. For example, the *Half-Earth Project* (www.half-earthproject.org) or the *Global Safety Net*[3] target 50% of Earth to be formally protected to halt biodiversity loss, reduce CO_2 emissions, and enhance natural carbon sequestration. To be optimally effective, these programs should aim to include the maximum breadth of species, habitats, and ecosystem services. Upon evaluating the diverse post-2020 conservation agendas, however, we were struck by a curious omission. Subterranean ecosystems—likely the most widespread non-marine environment on Earth[4,5]—were unfortunately overlooked.

Whereas we don't know the true global extent of the subterranean biome[5], a rough estimation using geospatial data of relevant geologic substrates suggests that it covers at least 19% of the terrestrial surface. Of this, only 6.9% overlaps with currently protected areas (Figure 1), which is a rather low percentage for an ecosystem type. Importantly, this estimate does not account for the vertical dimension of subterranean ecosystems.

The omission of subterranean ecosystems from global biodiversity and climate change agendas marginalizes their ecological and economic importance. From a biodiversity point of view, these systems harbor a great diversity of specialized organisms that are of interest from both a conservation and evolutionary perspective (Figure 1). Subterranean species are often short-range endemics (occurring within a single cave or geologic formation) and some represent ancestors of faunas that disappeared from surface habitats. Thus, they account for a considerable proportion of global taxonomic, phylogenetic, and functional diversity that is currently imperiled by human activities[4], especially climate change[6].

Being adapted to environments with limited seasonality, stable temperatures, and a near water-saturated atmosphere with a negligible evaporation rate[6], most of these species have lost the physiological mechanisms to withstand rapid environmental fluctuations[7,8]. Although a lag effect may be expected with subterranean temperatures, compared to adjacent surface ecosystems, climate change is predicted to alter conditions that these sensitive species currently rely upon[6]. Temperature increase, drought-related stressors, and ecological shifts of surface ecosystems (e.g., desertification) are all projected to alter hydrological regimes and pervert subterranean conditions—rendering some suitable habitats unsuitable. When considering that most specialized subterranean species are unable to escape the effects of climate change—due to geographical, phenological, and behavioral constraints—subterranean ecosystems may represent dead-end traps for their obligate inhabitants[6].

By threatening subterranean biodiversity, climate change will in turn affect the provisioning of crucial ecological services to humankind[4] (examples of services in Figure 1). Perhaps most importantly, an estimated 95% of the world's available liquid freshwater supply is groundwater and over one-quarter of the human population is completely or partially dependent on it[9]. Bacteria and invertebrates play a key role in maintaining clean groundwaters as they are responsible for the carbon turnover, the attenuation and degradation of harmful contaminants, and may even eliminate pathogenic viruses and microorganisms[10]. Globally, the human demand for groundwater is ~3.5 times the actual volume of aquifers[11], and this situation will only worsen as the human population keeps growing and the intensification of drought events will increase the demand of groundwaters for agricultural irrigation[9,12]. The combination of these and other climate change-related stressors, such as saltwater intrusion in coastal aquifers, are predicted to eliminate or constrict aquatic subterranean freshwater habitats, threatening subterranean biodiversity and reducing water availability for human use[12,13].

Another well-documented example of ecological service is provided by cave-roosting bats. Nearly 150 bat species use subterranean habitats (IUCN Red List, Version 2020-3). Of these, many provide important ecological services including seed dispersal and pollination of both timber and food crops, as well as the consumption of agricultural pests[14]. Rising temperatures may cause current summer roost caves to become too warm impeding maternity activities, as well as arouse bats from hibernation during times of low prey availability[15]. These changes could facilitate further population declines, which would spur a reduction in bat ecological services.

As subterranean ecosystems have been lamentably overlooked, perhaps the aphorism of 'out of sight, out of mind' has driven both scientific interest and policy decisions. It is therefore critical to develop a strategic plan to monitor subterranean habitats and biodiversity, which can be integrated into current global conservation targets. This strategy should include the identification of a suite of bioclimatic indicators to safeguard key ecological services and highly biodiverse subterranean communities.

This year marks the *International Year of Caves and Karst* (http://iyck2021.org). Serendipitously, we hope 2021 will also represent an inflection point in global decision making concerning subterranean habitats. It is high time these critically important ecosystems assume their rightful place in global biodiversity conservation strategies and climate change mitigation agendas.

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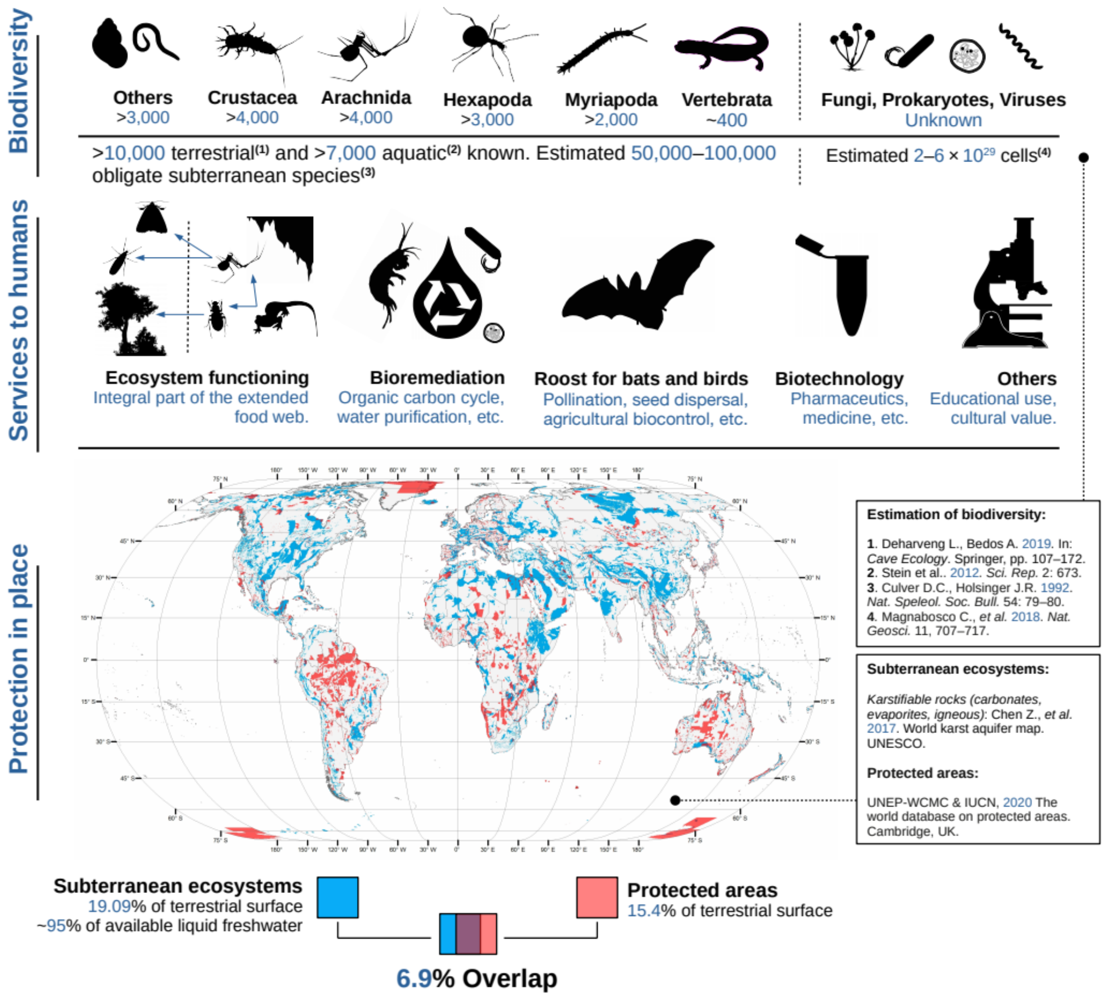

Figure 1. Biodiversity, ecological services, and current status of protection of subterranean ecosystems. The extent of subterranean ecosystems was calculated by combining geospatial layers of the primary strata supporting subterranean habitats —karst and lava fields. An estimation of subterranean diversity and examples of ecological services were based on recent literature (refer to literature cited in both the figure and main text).