Chapter 14
Species Diversity Within and Among Ecosystems

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Glossary

Biodiversity	The variability among living organisms from all sources and the ecological complexes of which they are part biodiversity includes diversity within species between species and of ecosystems.
Ecosystem	A dynamic complex of plant, animal, and microorganism communities and their nonliving environment interacting as a functional unit.
Ecosystem service	The benefits people obtain from ecosystems these include provisioning services such as food and water regulating services such as flood and disease control cultural services such as recreation or spiritual benefits and supporting services such as nutrient cycling.
Population	A geographic entity within a species that is distinguished either ecologically or genetically.
Species (biological species concept)	Interbreeding natural groups whose members are unable to successfully reproduce with members of other such groups.

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Definition of Species Diversity

Species diversity is a function of species richness, the number of species in a given locality and species evenness, the degree to which the relative abundances of species are similar [1, 2]. While this notion may be easy to conceptualize, it has proven difficult, and at time contentious, to quantify [1, 2]. Commonly used methods include constructing mathematical indices known as diversity indexes (the Shannon, Simpson, and Margalef indexes being the most widely used) or comparing observed patterns of species abundance to theoretical models [3]. There is no single best metric and often commonly used ones are chosen because they are familiar and not necessarily because they are the most appropriate [1]. The scale of assessment may range from within a single site or habitat (known as α diversity) to the difference between two or more sites (β diversity) [4], which can then be combined to give γ diversity – the diversity of the landscape. Early research tended to be concentrated on largely α diversity, but there has been a marked increase in studies investigating β and γ diversity during the last decade [1].

The species richness aspect of diversity is often considered the iconic measure of biodiversity since it is well defined and aligns with our intuitive sense of the concept [1, 5]. As the species level is the level at which living organisms are most widely known, species have become the major taxonomic rank for describing biodiversity. Along with populations, it is also the level that most scientists, managers, and policy makers use when referring to biological diversity, and it provides a useful means for both monitoring and priority setting [6]. As the species level is one of three fundamental levels of biodiversity (the others are the genetic level and the ecosystem/community level), species diversity is thus an important component of conservation. This entry will refer to species diversity in the less restrictive sense, that is, the variety of species that inhabit our planet.

Introduction

Ever since naturalists began classifying living organisms, there has been no consensus on how best to define a species [7]; Mayden [8] listed 24 different named species concepts and in a partial listing, Mallet [9] indentified 15. This longstanding failure of scientists to agree on how to identify species is commonly referred to as the species problem, with taxonomists being described as either “lumpers” or “splitters” with the former approach resulting in lower numbers of species and the latter higher. However, despite this proliferation of definitions, most taxonomists agree that species represent a distinct genetic lineage, interact with the environment in similar ways, and are reproductively compatible [1, 5, 7]. More importantly, whether based on gene flow, ecological separation, or morphological distinctiveness, most concepts tend to give similar results due to the independent evolutionary history that has resulted in unique morphological, ecological, and

Table 14.1 Estimates of number of eukaryote species globally, following [10]

Estimate	References	Method
30 million	Erwin [17]	Extrapolation from samples
3–5 million	Raven [18]	Ratios known: unknown species
10–80 million	Stork [19]	Extrapolation from samples
4.9–6.6 million	Stork and Gaston [20]	Ratios known: unknown species
1.84–2.57 million	Hodkinson and Casson [21]	Ratios known: unknown species
5 million	Hodkinson [22]	Ratios known: unknown species
4–6 million	Novotny et al. [23]	Extrapolation from samples
7.4–10 million	Mora et al. [16]	Extrapolation from samples

reproductive characteristics. In addition, most populations within a species share common ancestors with other populations in the very recent past, which in turn causes them to not be significantly differentiated [10].

Since the middle of the twentieth century, the most commonly accepted definition has been the biological species concept [10], which defines a species as a group of interbreeding natural populations whose members are unable to successfully reproduce with members of other such groups [11]. As species based on this definition have natural and objective boundaries due to gene flow [12], they provide natural units for biodiversity assessment [5]. While the approach of classifying species will influence both conservation priorities and the scale of intervention [5], the important thing for conservationists is that the commonly understood units can be defined and interventions implemented and assessed. There will always be issues with using species as a basis for biodiversity assessment, but many of these can be overcome [5, 10, 13].

The next question that often arises is how many species exist on Earth. While there are no reliable estimates for prokaryotes [10, 14, 15], many estimates exist for eukaryotic species. Recent studies [16] predict ~8.7 million species globally, of which ~2.2 million are marine species. Earlier estimates have varied greatly, with most falling between five and ten million (see Table 14.1). However, these estimates could be much higher if poorly known groups such as deep-sea organisms, algae, or fungi have more species than currently believed [10]. Incomplete sampling, lack of robust extrapolation approaches, controversy over the underlying assumptions, and subjectivity are all cited reasons for the uncertainty [16]. However, with only around 1.7 million species currently described [16] and only 15,000 newly described species each year [25], the key point is that a major knowledge gap still exists in this area; there is a likelihood of losing species to extinction before ever describing them.

Patterns of Species Diversity

Despite the uncertainty around how to define a species and the total number of species on the planet, the diversity of species is evident in the world around us. Species are unevenly distributed across the globe [10, 26] in terms of both geography and taxonomic groupings, with a disproportionately large number of species in the Class Insecta. It is very difficult to estimate this variability, as data are limited for marine and fresh water ecosystems and for non-vertebrate species, but there are around 10 plant species and at least 100 invertebrate species for each vertebrate species. Despite their low numbers compared to invertebrates, considerable datasets have been compiled for vertebrates, allowing numerous patterns of variations to be explored [10], although the extent to which these patterns can be generalized remains unknown [27].

One of the most obvious patterns is that for virtually all taxonomic groups, species richness tends to decrease from the tropics to the poles [28]; the tropics hold much higher species richness than do temperate, boreal, or polar regions. This is more so than would be expected on the basis of area alone [10], although it is complicated by physiographic and climatic factors such as mountain ranges or rainfall patterns. There is also a broadly similar spatial distribution of diversity between taxa, where differences seem to be driven by particular biological traits [10, 29]. In general, these differences will increase with increasing evolutionary distance between taxa [30]. Patterns of marine and freshwater species richness are less understood, but studies [31, 32] have demonstrated a latitudinal gradient in the shallow water benthos, with decreasing richness toward the poles.

There are also patterns of endemism and evolutionary distinctiveness that are important aspects of species diversity, as species with long and independent evolutionary histories and few surviving relatives contain irreplaceable genetic diversity. Most species have small range sizes [33], which tend to co-occur in centers of endemism [10, 31]. Centers of endemism are also concentrated in the tropics, with overlap, at certain scales, across birds, mammals, and amphibians [34] and a similar pattern is expected for plants [35]. However, this pattern does not appear to represent the situation for invertebrates or microorganisms [10]. There is enormous variation between species in terms of the evolutionary age [36]. Evolutionary distinctiveness among species can be explored using taxonomic relationships and as with species richness, the available data indicates that tropical rainforests are regions with the greatest number of taxa with the longest independent evolutionary history [37].

Vertebrate Species Status, Trends, and Threats

Conservation assessments have been primarily carried out for vertebrates as the conservation community tends to use these species as flagships or indicators of ecosystem health and global biodiversity. Therefore, this section will focus on vertebrate species, as sufficient data exists on the status and trends of the world's mammals, birds, amphibians, and cartilaginous fishes, and weighted approaches can be used to gain an understanding for reptiles and bony fishes [38]. Other taxonomic groups will not be discussed as there is not currently sufficient data for a global assessment. However, vertebrates represent only 5% of animal species and a fraction

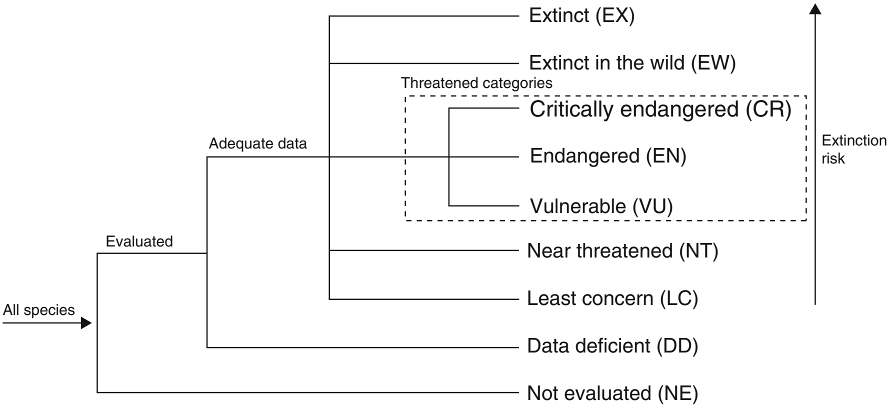

Fig. 14.1 The IUCN red list of threatened species™ provides taxonomic, conservation status, and distribution information on species that have been globally evaluated using the IUCN red list categories and criteria

of the world's overall species [39]. Recent efforts to assess whether vertebrates trends and patterns can be used to extrapolate for other taxonomic groups are ongoing and show promise, with initial assessments indicating that the threat levels seen in invertebrate groups are not dissimilar from that of vertebrates [40].

The IUCN Red List of Threatened Species is the most widely accepted standard for assessing species' risk of extinction [41]. The IUCN Red List assesses species according to five quantitative criteria and classifies them into one of eight categories (see Fig. 14.1). Regular assessments of taxonomic groups provide information on trends in extinction risk, known as the IUCN Red List Index (RLI). The RLI considers species classified as Critically Endangered, Endangered, or Vulnerable to be threatened with extinction and explicitly accounts for Data Deficient species. Comprehensive datasets exist for mammals [42], birds [43, 44], and amphibians [45], while sampled assessments can be used for other taxa [38] (Fig. 14.2).

Trends in vertebrate populations have been measured using the Living Planet Index, a global biodiversity indicator that tracks changes in vertebrate populations in the wild. It contains data on species trends from 1970 to 2005 and is calculated by aggregating population time series for each taxonomic group where data is available [46]. However, results for individual classes are at this point considered preliminary and conservative due to limited data or data biased toward temperate regions [38].

Mammals

Mammals are found across the world's terrestrial and aquatic ecosystems, with South American, sub-Saharan Africa, and Southeast Asia containing the highest concentrations of species of terrestrial mammals. The highest species richness of

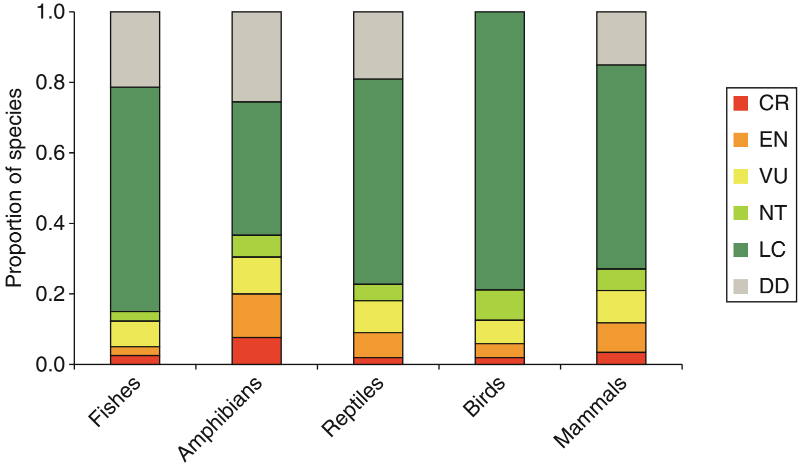

Fig. 14.2 Vertebrate species by IUCN red list categories [38]

terrestrial mammals is found in the tropical rainforests of Brazil and Indonesia and for aquatic mammals, the continental coastlines are the areas of the highest species richness; 21–36% of mammal species are currently threatened with extinction and the highest proportion of threatened species are found in the Monotremes (egg-laying mammals) and Perissodactyla (odd-toed ungulates). Countries with high numbers of threatened terrestrial mammal species include Mexico, Indonesia, Brazil, Papua New Guinea, and Vietnam. For marine mammals, the highest species richness of threatened species is found around the coastal regions of Asia, Japan, North Atlantic, and North Pacific [38, 42].

The LPI shows an overall reduction of 25% for terrestrial mammals. Marine mammals are omitted in the analysis due to sparse data; however, cetaceans have experienced a well-documented decline [47]. Mammal species are threatened from deforestation and coastal development, especially logging, wood harvesting, and smallholder farming. Overexploitation, particularly in the form of hunting for sport, subsistence, or use in traditional medicines, is also a threat to numerous species [38, 42].

Birds

Birds are found on all seven continents, with many migrating thousands of kilometers every year between breeding and wintering grounds. Habitats with high number of bird species include forests, shrubland, grassland, savanna, and inland wetlands [44, 48]. The Neotropics – specifically Colombia, Peru, Brazil and Ecuador – hold the highest numbers of bird species, followed by the Afrotropical, Indomalayan, and Australasian realms. Between 12% and 13% of bird species are currently threatened with extinction; areas with particularly high densities of threatened bird species are the tropical Andes, the Atlantic forests of Brazil, the Eastern Himalayas, Eastern Madagascar, and the archipelagos of Southeast Asia [38, 44].

The LPI shows an overall decline of 8% for birds and 28% for tropical birds alone. The main threats to birds are the spread of logging, wood harvesting, and agriculture in addition to the impacts of invasive alien species. Residential and commercial development, hunting, and pollution are also having serious impacts on bird populations globally [38, 44].

Amphibians

As amphibians are dependent on water for reproduction and other stages of their life cycles, the majority are found in tropical moist forests or freshwater ecosystems. Amphibian species richness is highest in the Neotropical regions of South and Central America and the countries with the highest species richness are Brazil, Colombia, Ecuador, and Peru. The Southeastern USA also has high species richness due to the large number of native salamander species. Roughly 30–56% of all amphibian species are currently threatened with extinction [45]. Among vertebrates, they have the highest proportion of Critically Endangered species and highest number of recent extinctions. The highest species richness of threatened amphibians is found in the dense tropical and subtropical forests of the Northern Andes, Caribbean, Western Ghats, Malaysian Borneo, and West Africa [38, 45].

There is only limited data on amphibian population trends, so the LPI result of an 80% decline should be treated with caution [38]. There is, however, a great deal of supporting evidence that amphibian species have suffered a major decline since the 1970s [40, 45, 49, 50]. Their aquatic habitats are under great human pressures, which included rapid deforestation, habitat degradation, pollution, and overuse of water. In addition, the emergence of the chytrid fungus, *Batrachochytrium dendrobatidis*, is another major threat. First described in the 1990s, the fungus is now found on every continent inhabited by amphibians and evidence suggests that it is responsible for causing mass mortalities among many populations [51, 52].

Fishes

The West and Central Indo-Pacific, South China, and Coral Sea are the areas of the highest marine fish species richness, while Southeast Asia, Eastern Africa's Great Lakes, South American Amazonia, and the forest of Central Africa have the highest species richness of freshwater fish [38]. Of the world's fish species, 41% are obligate freshwater, 58% are obligate marine, and the remaining 1% can tolerate both systems. An assessment of a representative sample of fish species suggests that between 12% and 34% are currently threatened with extinction. The highest species richness of threatened marine fishes is found in the Indo-West Pacific, Central Indo-Pacific, South China, Coral, Caribbean, and Mediterranean Seas, and the highest species richness of threatened freshwater fish species is found in Southeast Asia [38].

The available data for the LPI for freshwater fish indicates a rapid and steady decline in population abundance approaching a 65% reduction. Marine data are limited, but indicate a gradual decrease of 20% in the number of marine fish populations [38]. The main threat to fish species is overexploitation and pollution; aquatic habitats are routinely treated as limitless sources for human consumption [53, 54]. Over 85% of the world's fisheries are either recovering or fully or partially overexploited [55]. In addition, freshwater fish have been particularly negatively affected by pollution and habitat alteration caused by damming and water management activities such as abstraction for agriculture [56].

Reptiles

While reptiles are the dominant vertebrate of arid systems, like other vertebrates, the highest species richness is found in tropical forests. Indonesia and the Congo Basin have the highest species richness of reptiles. Marine reptiles, such as sea snakes, turtles, and crocodiles, are found in the highest concentrations in the West and Central Indo-Pacific and the South China and Coral Seas. An assessment of a representative sample of species suggests that between 18% and 32% of reptile species are threatened with extinction, although this varies greatly between groups [38]. For example, a high proportion of crocodilians are threatened compared with a relatively lower number of snakes [57]. The highest species richness of threatened reptiles is found in Southeast Asia and the Ganges basin [38].

The available trend data for the LPI for reptile species indicates that the number of reptiles has declined by 7% [38]. However, this figure for the whole class may mask the decline in certain orders such as turtles and tortoises, which have seen large declines in regional-scale analysis [57]. Habitat loss is the greatest threat to reptiles and is principally in the form of agricultural expansion, logging, and urban development. Hunting, trapping, and overharvesting for consumption and the pet trade are particular threats, especially to turtles and tortoises [58] (Fig. 14.3).

Link Between Species and Ecosystem Function

A key topic in ecology is investigating how the diversity and composition of species in an ecosystem is related to its function. Considerable research has gone into answering this question [59] and ecological theory supports the notion that ecosystem function, and the resultant goods and services, depends on biodiversity. It is

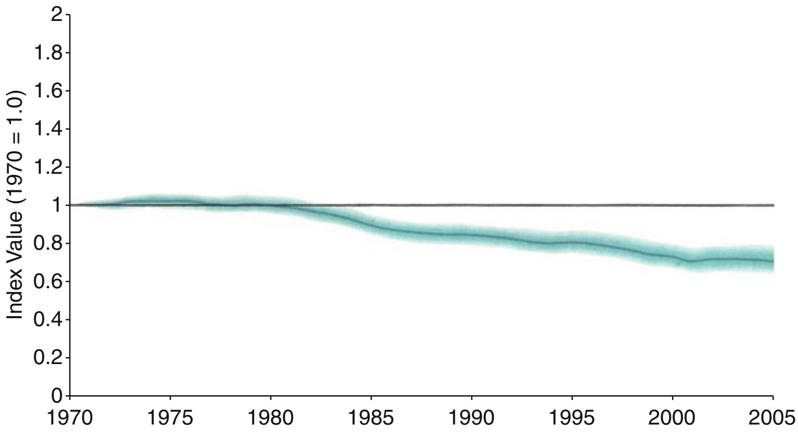

Fig. 14.3 Living planet index for vertebrates. Index value shown in bold; shaded area shows 95% confidence limits [38]

generally predicted that a decrease in biodiversity will result in a reduction of ecosystem function, which will in turn lead to the loss of ecosystem goods and services [60–62]. While there is still work to be done to describe the exact nature of the relationship [63], evidence suggests that species richness, functional characteristics, composition, and interactions influence ecosystem function [64].

The greatest amount of research in this area has focused on the relationship between species richness and ecosystem function [65], with the relationship usually reported as being positive [64]. Evidence suggests that species-rich communities have greater interspecific variation in response to changes and provide more temporally stable ecosystem services [66]. In experimental systems, it has been proven that productivity, nutrient retention, and resistance to invasion and diseases, all tend to increase with increasing species richness [67].

Interactions among species, such as competition, mutualism, and predation, are also crucial to ecosystem functioning [67] and may be more important than species richness [68]. Direct interactions between plants and fungi, plants, and animals, and indirect interactions involving more than two species are essential for ecosystem processes such as transfer of pollen and seeds, transfer of plant biomass production to decomposers or herbivores, construction of habitat complexity, or the spread or suppression of plant, animal, and human pathogens [67]. Interactions between different species trophic levels are also key to regulating the provision of ecosystem services [69]. Certain combinations of species are complementary in their patterns of resource use and can increase average rates of productivity and nutrient retention [64].

Species' functional characteristics also strongly influence ecosystem properties. The loss of species such as ecological engineers or keystone species with unique functional characteristics may have profound effects on ecosystem function [71]. Species composition also plays an important role in ecosystem processes and extinctions of local populations, or their reduction to functionally extinct, can dramatically affect regulating and supporting ecosystem services [71].

Species Loss and Extinction

It is clear that as more species and/or the variability within species disappears, significant loss of ecosystem function, and hence ecosystem goods and services, may occur. While the evolution of species and the extinction of others is a natural process, current extinction rates are estimated to be between 100 and 1,000 times greater than they were in the distant past and future rates may be 10–100 times what they are today [10, 34]. Even among lesser threatened taxa, for example, birds, current extinction rates are several orders of magnitude higher than the natural or background rate. Roughly one-fifth of the world's vertebrates and plants are threatened with extinction [38, 72], and in addition to individual species, entire lineages or ecosystems are threatened [45, 73]. Current rates of population extirpation are probably at least three orders of magnitude higher than species extinction rates [74]. In addition, changes in the relative abundance among species are also capable of causing important changes in ecosystem function [75].

The main cause of extinction across all vertebrate groups is habitat loss or degradation – primarily driven by agricultural development and logging – followed by invasive species and human overexploitation [38, 72]. However as the impacts of climate change increase, it will likely be the greatest driver of extinctions this century. Climate change has already been proven as a cause of species extinction [76] and may likely be the greatest driver of extinction this century. As more distributions shift, it is predicted based on midrange climate warming scenarios for 2050 that 15–37% of species will be committed to extinction, with the most severe impacts resulting from synergistic interactions among a range of threats [77, 78].

Conservation of Species and Ecosystems

Invasive species and human-caused extinctions are already altering ecosystems; there are few places left on the planet that have not been affected by human impacts [79, 80]. Even minor losses may reduce the capacity of ecosystems to adjust to changing environments. As it is often difficult, expensive, or impossible to fix or reverse these changes with technological solutions [64, 81], it is crucial that the diversity of our planet's species and ecosystems is conserved. There are several levels of approach and the appropriate one will depend on the specific goals and resources available. The species level has been the traditional focus of conservation planning and action. Common frameworks include IUCN Species Action Plans and Species Conservation Strategies, which focus on assessing species and making conservation recommendations, and Range-wide Priority Setting, which is designed for widely distributed species. Other approaches include the EDGE approach, which combines IUCN Red List data on threats with species evolutionary distinctiveness to focus on conserving threatened species with few remaining relatives [82].

Conservation approaches at other levels, such as landscape/ecosystems, are also widely used. Examples include Conservation Action Planning [83], which often focuses on a target landscape, and the Ecosystem Approach, which puts natural resource use at the center of decision making [84]. However, even at the ecosystem/ landscape level, conservationists still use species, often iconic and charismatic species ones referred to as flagship species, to act as ambassadors for conservation of the wider area. These species are also a good way to begin engaging with the public, an important part of modern conservation. If people feel a connection to the natural world, they will be more willing to conserve it [85].

Whatever the chosen approach, it must be based on sound science and have a strong conceptual framework to guide action on the ground. Included in this framework should be significant capacity-building component to enable long-term continuation of responses capable of keeping pace with increasing threats, especially climate change. While there have been past conservation successes [73], the conservation community needs to focus more on coordinating large-scale strategic conservation plans around specific objectives. National Biodiversity Strategies and Action Plans, required by Convention on Biological Diversity member countries, have the potential to be very effective, if technical capacity and financial resources are developed to support their creation and implementation [90].

Conclusions

While there is disagreement about the definition and number of species, it is known for sure that species are the building blocks of ecosystems, and their diversity within and among ecosystems is essential to maintaining its function. Species are under threat from numerous anthropogenic factors including habitat loss, overexploitation, introduced and invasive species, and climate change. Current extinction rates are magnitudes higher than those of the past and no one knows for certain how many species the planet can afford to lose before there will be major implications for humanity. As technological solutions to lost or degraded ecosystem services are often expensive, difficult, or even impossible, there is clearly a need to conserve and sustainably manage our ecosystems and the species within them in order to maintain biodiversity and its practical benefits to humanity. However, the current level of conservation action is far outweighed by degree of threat. To halt species loss, there is an urgent need to scale up conservation action. While there have been conservation successes in the past, a coordinated and increased national- and global-level response is urgently need to halt the loss of global biodiversity.

Future Directions

The ecology of species and ecosystems is incredibly complicated and there are still many knowledge gaps regarding species diversity and its exact role within ecosystem function. Further research is needed to more fully explain this relationship and inform conservation action and policy. However, urgent action is also needed to conserve species as it can be confidently predicted that there is already a movement toward the next mass extinction [50, 86]. This is especially critical as the year 2050 is approached when the Earth will need to provide enough natural resources for an estimated 9.2 billion people [87]. Addressing the biodiversity crisis and all its consequences for humanity requires rapid movement toward governance structures and economic systems that encourage the sustainable use of Earth's natural resources. If this effort is to be successful, it cannot be limited to traditional conservationists; it must have the strong support of society as a whole and include leaders from a range of sectors such as engineering, medicine, finance, communications, business, and the arts.

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