Journal of
Zoological and Botanical Gardens

Review

Centers of Endemism and The Potential of Zoos and Botanical Gardens in Conservation of Endemics

Carsten Hobohm [1,*] and Nigel Barker [2]

[1] Ecology and Environmental Education, University of Flensburg (EUF), 24943 Flensburg, Germany
[2] Department of Plant and Soil Sciences, University of Pretoria, Private Bag X20, Hatfield 0028, South Africa; nigel.barker@up.ac.za
* Correspondence: hobohm@uni-flensburg.de

Abstract: Knowledge about ecological conditions and processes in centers of endemism (CoEs) is still limited with respect to various systematic groups of organisms, ecosystem types, ecological conditions, and ecosystem services. We review the characterization, identification, and meaning of CoEs. Endemics play an increasing and prominent role in nature conservation monitoring and management and in the organization of zoos, aquaria, and botanical gardens. We examine the importance of different groups of organisms and indicators for the characterization of endemic-rich regions, e.g., with regard to the richness of endemics per region and degree of endemism, the importance of heterogeneity in space, continuity in time, isolation, and ex situ management for the survival of endemic species. Currently, conversion of land cover and land use change are the most important causes of biodiversity decline and extinction risk of endemic and endangered species. These are followed by climate change, including severe weather, and then natural processes such as volcanism, landslides, or tsunamis. For conservation purposes, the management of regional land use, zoos, aquaria, botanical gardens, and social aspects of the diversity of endemics and CoEs have to be taken into account as well. We find that the ex situ representation of endemics in general is limited, and conservation networks in this regard can be improved. We need better answers to questions about the relationship between ecoregions, CoEs and regional awareness of endemism, which is linked with human culture including aesthetics, well-being, health, and trade.

Keywords: heterogeneity in space; spatial scale; land cover; continuity in time; isolation; ex situ conservation

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Citation: Hobohm, C.; Barker, N. Centers of Endemism and The Potential of Zoos and Botanical Gardens in Conservation of Endemics. *J. Zool. Bot. Gard.* **2023**, *4*, 527–548. https://doi.org/10.3390/jzbg4030038

Academic Editors: László Bakacsy and Ágnes Szepesi

Received: 10 May 2023
Revised: 9 June 2023
Accepted: 14 June 2023
Published: 13 July 2023

1. Introduction

The start of research on endemism and endemics in a macroecological context can be dated back to the transfer of terms from medicine to biogeography by De Candolle in 1820 [1–3]. Interest in the topic increased along with investigations of ecological and evolutionary questions on one hand and of declining biodiversity, an increasing number of threatened species and Red Lists worldwide on the other [4–8].

Meanwhile, neo-, paleo- (palaeo-), patro-, schizo-, apo-, hyper-, micro-, narrow, stenochorous, local, regional, national, supranational, and more or less widespread endemics, biodiversity hot spots, ecoregions, and CoEs have been defined and identified with respect to biome, spatial scale, habitat type, systematic level, and taxonomic group (e.g., [9–13]). As a first approximation, most of these terms represent biogeographical labels, comparable, e.g., with neophyte, indigenous, or alien/invasive species [14]. The evolutionary history, ecological conditions, or biological traits of range-restricted organisms is secondary, and it may be that taxa with a small range represent other ecological conditions or biological traits than widespread members of the same taxonomic group [15–18]. Rare species can be common where they occur [19], and niche specialization does not necessarily explain this result. However, there are few studies comparing rare and common congeners [20], and the measures of attributes were so varied that it was not possible to compare such studies in order to assess if there is any generalized cause of rarity [21,22]. Rarity is also scale-dependent [23], a finding that has implications for the processes used to assess the global and regional endangerment of species.

Niche specialization and degree of distribution have been combined to provide an assessment measure of rarity, recognizing seven possible different dimensions of rarity [24,25]. This approach has not been widely used, but it does provide a unique insight into rarity and has been used for plants [26–28] and a diverse range of animals (e.g., [29,30]).

The rarity of individual taxa on its own is no indication of levels of endemism, nor does it allow for the identification of centers of endemism. The link between the rarity and richness of a region needs to be made but only when richness is controlled for [31]. An endemic aligns with the idea of rarity [32], but endemism does not necessarily imply rarity as it is scale-dependent. These authors also consider the primary source of information on species rarity and endemism to come from taxonomists, but ecologists have perhaps done more to explore aspects such as traits, niche, and other aspects of rare and endemic taxa.

The whole inhabitable area of the Earth can be divided into ecoregions with high or low concentrations of endemics [33,34]. There are now countless checklists, floras, and faunas providing information about endemic species and regions, as well as an ever-increasing number of publications focusing on patterns and processes, evolutionary and genetic/phylogenetic analyses, and ecological and conservation goals [35–38]. Regions with high numbers of endemic taxa often show high spatial heterogeneity in combination with long temporal continuity, e.g., relatively stable climate conditions [39–43]. This raises several questions: is it possible to disentangle the importance of spatial heterogeneity vs. continuity through time [44–46]? How are species compositions and endemism influenced by spatial separation and isolation through time? What does this mean for our understanding of biogeographical patterns of endemism, ecosystem functioning, and nature conservation practices in both island regions and mainland areas [47–51]?

The knowledge of patterns and processes of endemism and CoEs is still limited with respect to different taxonomic groups and their evolutionary history including migration and dispersal under conditions of changing climate, landscape, and land use change. The meaning of specific conditions for survival at different spatial and temporal scales might differ from one place and taxonomic group to the other.

In a world of increasing pressure on biodiversity and declining diversity of native species in many regions, it is necessary to find serious political, technological, legal, and other solutions for the survival and well-being of endemic and threatened taxa on the basis of scientific knowledge, even if not all questions can be answered yet [52]. With this review, we want to mirror the state of the art and future prospects on the topic and emphasize the importance of research on CoEs in the context of ex situ nature conservation planning.

Figure 1 shows a schematic depiction of the relationship between the evolutionary diversification, number of endemics, and extinction risk of endemic and endangered taxa. It indicates that increasing and decreasing numbers of endemics and endangered species reflect different processes. Thus, the effects of land use and climate change on the assemblage and migration of the assemblage cannot simply be compensated by restoration.

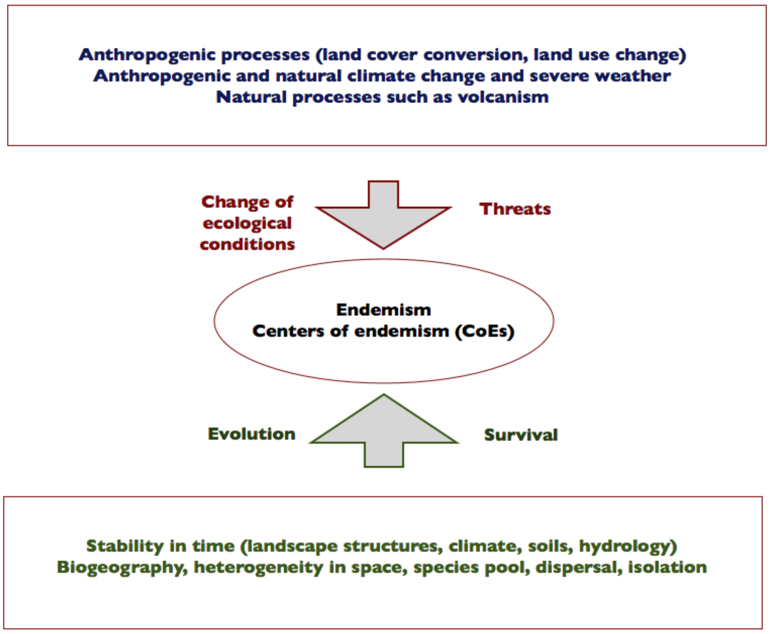

Figure 1. Endemism and centers of endemism between evolution/diversification and extinction risk due to anthropogenic and natural processes [53–57].

2. What Are Centers of Endemism?

If a region is characterized by high endemism, it is called a center of endemism (CoE). Examples are the Cape Floristic Region of South Africa or the Klamath–Siskiyou Mountains of northwest California and southwest Oregon [58–62]. If the original natural vegetation is additionally damaged, then it can be called a biodiversity hot spot [63]. However, the characteristics differ according to the region, composition of habitat types, group of organisms considered, and/or scientific mode of calculation and indication [61,64–67]. The key issue here is that there is no single or even subset of preferred methods or criteria for defining CoEs. In addition, the sampling bias and density can skew data and counts, resulting in misidentified CoEs or inaccurate decisions regarding the boundaries of CoEs. For example, after four years of field work, a new center of plant endemism in southern Africa was identified [5], a region already abundant in CoEs. However, after additional field work in a region adjacent to the new CoE, it was then noted that this recognition may have been premature [68].

There is a historical legacy linking chorology with the identification of biodiversity and CoEs. Chorology, e.g., in plants, has been applied at the family, genus, and species levels (e.g., [69]). The concept of chorology dates back to 1866 when it was used by Haeckel in relation to the dispersal of organisms away from a center of origin [70]. While chorology was initially a manual method of plotting distributions on maps and identifying iso-chores, more recent approaches have utilized computational power to analyze distribution data and identify CoEs (e.g., [71,72]).

A comparison of the numbers of endemic taxa or other indicators of endemism is, in principle, possible by comparing units of the same or of different range sizes. When comparing units of the same size such as quadrats of 100 or 10,000 square kilometers, the numbers of endemic taxa can be compared directly [73]. However, even grid cells of degree latitude/longitude have different range sizes in different latitudinal belts, and numbers of endemic taxa in this case are not directly comparable without mathematical correction. Meanwhile, many indicators for CoEs such as the number of endemics (E), endemics–area relationships (EARs), weighted endemism (WE and CWE), range size rarity (RSR), parsimony analysis of endemicity (PAE), proportion of endemics (S/E), Bykow's index of endemicity (BI), and others have been calculated by using different spatial scales and models [74–76]. The indication value of each method is limited, and the mode of calculation must be taken into consideration [77–81].

If, for example, the only native terrestrial mammal of the Hawaiian Islands is an endemic species (*Lasiurus semotus*), then the level of endemism is 100%. If it is a non-endemic species (*Lasiurus cinereus*), then there would be no species endemism in terrestrial mammals on the Hawaiian Islands (0%). With respect to its biology, this bat species has also been classified as endemic subspecies (*Lasiurus cinereus* subsp. *semotus*). This example shows that the level (ratio) of endemism cannot indicate the same as, for example, the number of endemics [82].

However, many ecoregions are labeled as CoEs because they have an obvious concentration of endemics, i.e., many more than in neighboring regions. This assumes that the sampling effort is uniform or equitable across the ecoregion. Nevertheless, all too often, sampling is biased, favoring easy access routes, etc. There is also the “diversity tracking” effect [83], where collectors of specimen and distribution data tend to visit places of known diversity so as to maximize their returns.

Due to methodological difficulties, and because of scientific underrepresentation, many groups of invertebrates such as insects or mollusks seem to rarely occur as endemics compared with vertebrates or vascular plants, which comprise the taxonomic groups mainly characterizing biodiversity hot spots and CoEs [84,85]. Thus, a stronger focus on these underrepresented groups might be appropriate to discover further centers of endemism.

3. Endemism in Different Groups of Organisms

In general, the transition zone between land and sea is the most effective border for the distribution of many phyla and most animal and plant species. Oceans are much older, longer inhabited by animals, and larger than, e.g., freshwater ecosystems, but the richness of marine fish species is comparable with the richness of freshwater fish species. Thus, after the niche occupation in rivers and lakes, the diversification rate in freshwater fish species must have been higher than in marine fish species [86].

While there are many more animal and plant species including endemic species in non-marine habitats (>75% of the whole species diversity), marine environments contain a much larger number of phyla including endemic phyla. Explaining this disparity was and still is part of a long-lasting discussion about origin and evolution, migration history, the meaning of dispersal, isolation, streams and currents, and continuity/change of ecological conditions [86–89]. In terms of marine biogeography, substantial leaps have been made in seeking or testing hypotheses of common causes to explain coincidental boundaries to distributions. For example, numerous phylogeographic studies on animal and algal taxa along the southern African coastline have indicated no clear congruent patterns in disjunctions, and when undertaken, dating analyses have not converged on a single historical period when such a disjunction came into being ([90] and subsequent papers by this author). Similar findings have been reported along the Australian coastline [84].

Various indicators such as the ratio of species/genera or genera/families, level or other indicators of endemism, indices of similarity, e.g., the Sørensen index and the Jaccard index, or molecular-genetic differences in phylogenetic diversity have been established to calculate the degree of uniqueness, isolation, or insularity of the species pool or assemblage [73,91].

Figure 2 shows current estimates of global species numbers of selected taxa with minima and maxima according to the species concept, calculation mode, and expectation of further discoveries.

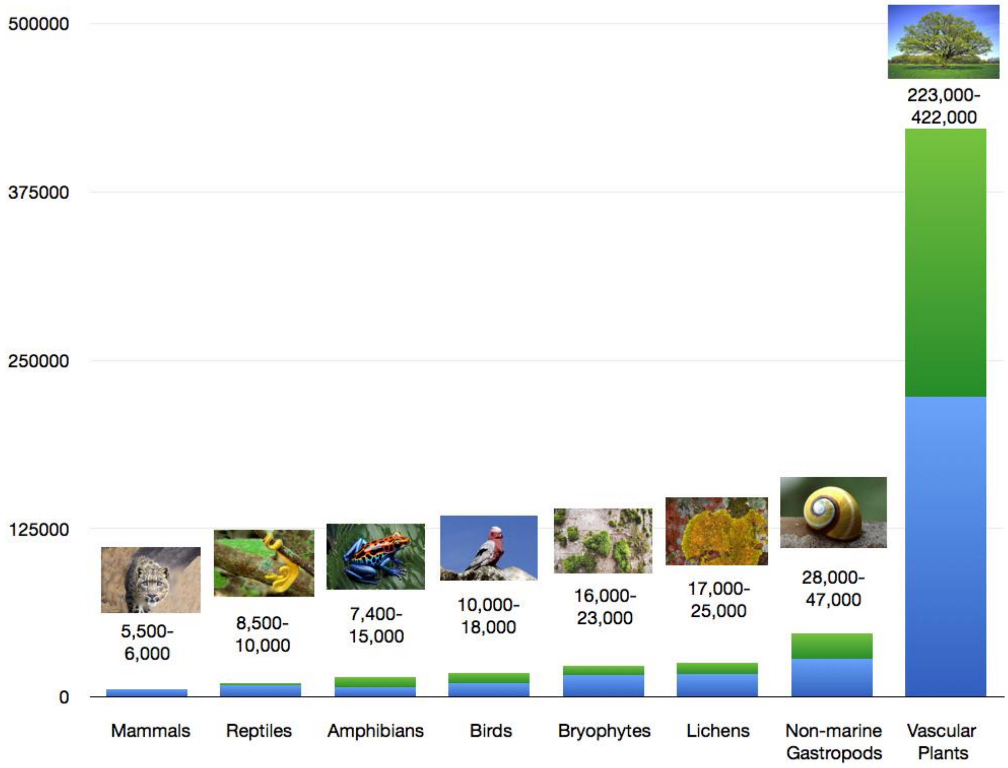

Figure 2. Global species richness of various groups of animals and plants [92–96]. Values are rounded; blue colors indicate minima, and green indicate maxima.

Taxonomic groups of animals, plants, or other groups differ in dispersal mode and speed of migration and thus have very different average range sizes. The degree of endemism in ecoregions and countries often increases, e.g., from lichens, bryophytes, and birds with relatively small percentage values to vascular plants and other vertebrates (intermediate level) to amphibians and non-marine gastropods, which regularly show much higher or the highest rates of endemism (Figures 3 and 4).

Despite a larger number of vascular plant species on Earth, the level of endemism in amphibians or non-marine gastropods at regional scales, for example, is often higher [97–100]. Even if range is one of the most curious concepts in biogeography, amphibian or non-marine gastropod species are on average more restricted than, e.g., birds. We assume that this has to do with the fact that they are slow and not able to fly (e.g., [101] and Figure 3).

Most members of the two richest plant families, Asteraceae and Orchidaceae, have the possibility of long-distance dispersal by wind (anemochory). They nevertheless contain many endemics at regional to continental scales. Endemic orchids are numerous in the tropics, whereas in many regions at higher latitudes and altitudes, endemic Asteraceae are regularly on top of the counts in checklists. Most endemics in these and many other families are pollinated by insects, which favors the occupation of, and evolution in, narrow niches (e.g., [102–104]).

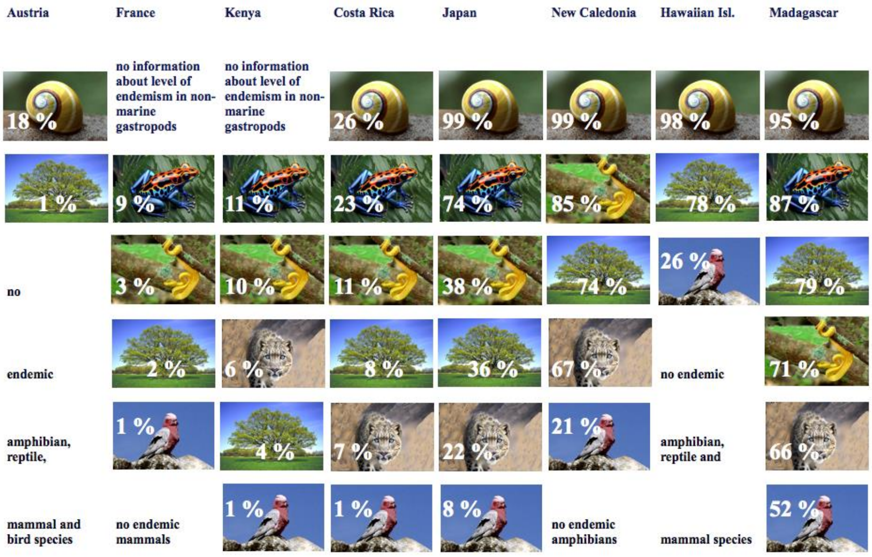

Figure 3. Levels of endemism in species of non-marine gastropods, amphibians, vascular plants, reptiles, mammals, and birds in selected regions/countries (collected or calculated from [97,98,105–108]).

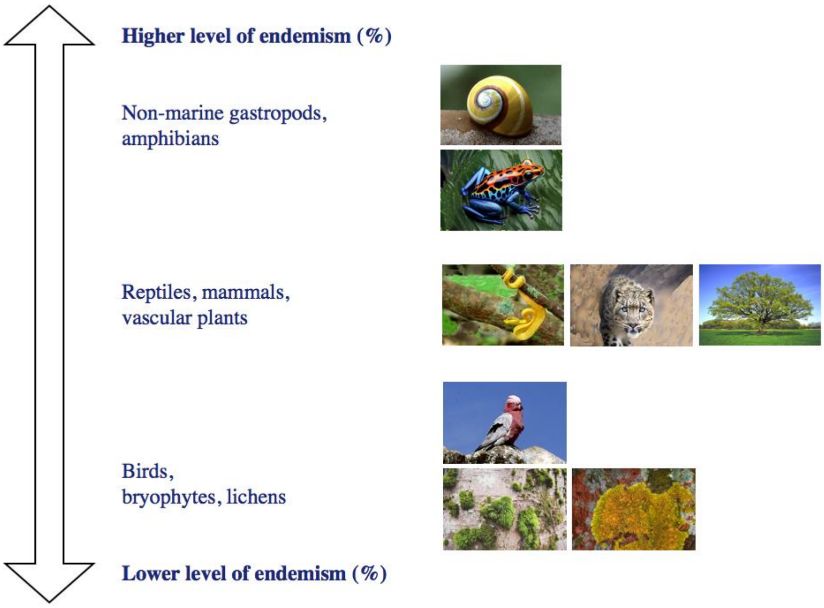

Figure 4. Hypothetical order of levels of endemism in different groups of plants and animals at intermediate spatial scales (for references, see Figure 3 and explanation in the text).

4. How Are Endemics Distributed and Related to Environmental Heterogeneity in Space?

Elevation of a region, number of predefined climate zones, and many other indicators have been used to calculate heterogeneity in space. Thus, various indicators of heterogeneity in space are available for biogeographical analyses (e.g., [109–113]).

Different groups of organisms show a latitudinal gradient with low numbers of species (S) and endemics (E) toward the poles and high numbers to the tropics [114,115]. This means that tropical and subtropical zones are richer in species and endemics than temperate or boreal–arctic regions, even if exceptions in several taxonomic groups have been discovered (e.g., [116–125]). Mountain ranges harbor higher numbers of endemic taxa than lowland areas of comparable size, longitude, and latitude [120–124]. There is also a well-documented mid-slope peak in diversity up elevational gradients in mountains termed the mid-domain effect [124–127].

Large species pools, CoEs, and phylogenetic diversity often represent the same ecoregions or overlapping areas [128,129]. Despite the large congruence between E, E/S, S, and other values characterizing CoEs, exceptions are numerous, and, e.g., maxima in various taxonomic groups characterize different regions [130] (Table 1).

Table 1. Putative world records of endemism in several taxonomic groups. World records of richness in vascular plant species per unit area, biomass, and productivity are included for comparison.

	Maxima	Mode of Calculation	Country/Region	Ecosystem (Dominant)	Climate (Dominant)
Endemism in mammals and birds plus reptiles [131]	>70	Numbers of endemics by terrestrial ecoregion	Eastern Madagascar	Rainforest	Wet tropical and subtropical
Endemism in birds [132]	92	E/S as percentage value	Hawaiian Islands	diverse	Humid tropical and subtropical oceanic
Endemism in freshwater animals (vertebrates and invertebrates) [97]	54	E/S as percentage value	Lake Baikal, Russia	Freshwater lake	Temperate continental
Endemism in fish, freshwater turtles, and crocodiles plus amphibians [131]	>150	Numbers of endemics by freshwater ecoregion	High Andes, western India, East African Rift Valley lakes	Wetlands and freshwater ecosystems	Tropical and subtropical
Endemism in cichlid fishes [97]	Up to 99	E/S as percentage value	Tectonic Lakes Tanganyika, Malawi, Victoria, Africa	Freshwater lake	Tropical
Endemism in land snails [98]	c. 100	E/S as percentage value (rounded)	Hawaiian Islands	Diverse	Humid tropical and subtropical oceanic
Endemism in vascular plants [99,100,133]	>80	E/S as percentage value	New Caledonia, Hawaiian Islands, Madagascar, St. Helena, New Zealand	Diverse	Subtropical and tropical oceanic
Endemism in vascular plants [134,135]	4.7–5.1 and 4–4.4	Relative distance of residual to regression (Res. E)	Mas a Tierra, Chile, and St. Helena	Forest	Subtropical oceanic
Endemism in pteridophytes [136]	37/31.7	Percentage of endemism/index of insularity	Easter Island	Reeds and grasslands replace the original tropical forest	Tropical oceanic/subtropical humid
Species richness in vascular plants [137]	942	No. of species per 10,000 m^2	Ecuador	Lowland rainforest	Humid tropical
Species richness in vascular plants [138]	115	No. of species per 10 m^2	Romania	Steppe meadow (currently grazed)	Temperate
Biomass [139,140]	1819 or 2844	tC ha-1 (above-ground biomass) or tC ha-1 (total biomass)	SE Australia	Eucalyptus regnans forest	Warm temperate
Productivity [141,142]	8.93–9.93	kg m-2 year-1 (dry matter)	Amazon	Swamps dominated by C4 grass Echinochloa polystachya	Wet tropical

Several islands and archipelagos distant from the mainland harbor high numbers of endemics and represent the highest levels of endemism. On the contrary, tropical and subtropical mainland regions often harbor many more species in total and higher phylogenetic diversity than comparable islands or archipelagos. This has to do with dispersal, biological connectivity, spatial separation, and genetic isolation effects through time [143].

Springs, lakes, rivers, fens, bogs, mountain tops, rocky outcrops, or areas with serpentine soils in terrestrial regions are ecologically more or less isolated habitat islands and separated comparably with true islands [144,145]. However, isolation is relative. Saltwater is a barrier for many taxonomic groups but a medium of dispersal, e.g., for marine animals and coconut (*Cocos nucifera*). Thus, habitat islands may only be islands under the current climates. They may well have once been more widespread and connected.

A preliminary list of hyperendemics, which are defined as species with an extremely small range of a single square kilometer or a maximum of 50 individuals [146], showed that the focus on these restricted endemics can elucidate the importance of habitat types and landscape units that are often located outside of already identified CoEs. For example, many small springs harbor freshwater and wetland gastropods with a rather restricted range.

5. How Is Endemism Related to Continuity, Change in Time and Isolation?

Species compositions and species richness of landscapes and regions reflect continuity and change of ecological conditions during the history, the length of time periods, and evolutionary speed. Specific modes of dispersal, migration routes, and the increase or decrease in the numbers of species depend on the distribution of water bodies and terrestrial land, i.e., on barriers and drivers of migration/dispersal. Distances to other water bodies or land masses are seen as important components to calculate the degree of isolation [147,148]. The similarity of ecological conditions, assemblages, and phylogenetic diversity are used to characterize the degree of uniqueness and isolation as well.

Ecological conditions and the amount of endemic plant species, e.g., of the higher mountain belts of the Macaronesian Islands, differ much more than, e.g., coastal habitats of the archipelago, and they are more distant [149–151].

Under stable geological, climate, soil, and hydrological conditions, the number of species increases via evolution and migration/dispersal. Isolation processes also favor the evolution of endemism. Isolation in a biogeographical context can be defined as a condition reducing or preventing genetic, social, and other biological aspects such as intraspecific and interspecific relationships and dispersal. Because of the strong isolation of a first propagule arriving at a new oceanic island, the survival of this species is highly questionable. This propagule must find adequate ecological conditions, must build a founder population, may overcome a genetic bottleneck, and so on. Isolation, on the other hand, reduces dispersal with the effect that mainland regions normally have higher numbers of non-endemics than ecologically comparable island regions. In general, both large species pools and isolation, which often show opposite patterns, favor the evolution of endemics [152–155]. In plants, there is a link between successful dispersal and polyploidy (e.g., [156,157]). Ploidy data are scattered (especially for endemics), but it would be an interesting line of inquiry to assess the levels of ploidy in endemics and widespread congeners and taxa in general.

According to the theories on adaptive dynamics and assembly optimization, optimization of resource use is one of the most important drivers for processes controlling ecosystem functioning, species composition, and diversity [158–163]. If processes and conditions of dispersal are reduced because an archipelago such as the Hawaiian Islands is located far distant from mainland areas and other archipelagos, then the evolution of new taxa can help to optimize the nutrient cycling and resource use. As a result, the total number of taxa (S) on isolated islands often is relatively small compared with mainland areas of the same range size and similar ecological conditions, the number of endemics (E) is high, and the level of endemism (E/S) is extremely high [164–166].

Because there is no other planet enabling life in our vicinity, all taxa on Earth are at the same time global endemics (S = E). The isolation is maximal, and the level of endemism is 100%. In general, high percentage values indicate strong isolation. The level of endemism of an archipelago is normally higher than that of each island belonging to the archipelago. This indicates stronger isolation for the whole archipelago in comparison with the islands belonging to the archipelago. However, the level of endemism of an island or archipelago depends on both the amount and composition of endemics and non-endemics. Furthermore, the composition of non-endemics normally differs from island to island. Thus, the level of endemism of an island can theoretically be higher than the level of endemism of the whole archipelago (Figure 3 in [167]).

Meanwhile, studies on the history of climate change at regional to continental scales, on refugia and microrefugia during glaciation periods, and climate continuity as a precondition for the evolution and survival of endemics are numerous. Dynessius and Jansen's work and theories are applicable here [168–170]. The relation between the number of endemics, the proximity to refugia, and climate continuity has often been pronounced and modeled. Moreover, the relative importance of time stability for evolution and survival is often hypothesized as higher than heterogeneity in space [171–174].

However, the change of ecological conditions is much more than climate change, and the discussion about the meaning of other components of temporal change in the environment is ongoing [175,176].

6. How Important Are Zoos and Botanical Gardens for Endemics and Vice Versa?

Mankind's relationship with animals kept in domestication for a specific purpose dates back millennia, and this relationship and purpose has changed over time [177]. Zoos, aquaria and botanic gardens have been considered as "Arks" where taxa are kept and distributed between such organizations with the aim of sustainable "insurance" populations, which can then be used for augmentation of existing small populations in the wild, or reintroduction into the wild where species are extinct in nature [178–180]. Thus, the role and function of zoos over the last four or five decades has resulted in a much more conservation-focused approach [181]. However, the global distribution of zoos is disproportionately biased toward the global west first-world countries (https://en.wikipedia.org/wiki/Zoo#/media/File:World_zoo.png; accessed on 20 April 2023), generally distant from areas of faunal endemism and species in need of ex situ and in situ conservation.

Zoos are considered to be "ethically contested institutions" in terms of their existence as well as their aims, policies, and practices, which are underpinned by regulations and commitments to shared values of animal welfare and species conservation [182]. The authors argue that these values may be in tension, resulting in decisions that fulfil some aims at the expense of others or result in unsatisfactory tradeoffs. Among other conclusions, they suggest that zoos should hold a higher number of threatened taxa than currently in captivity and that species that do not require so much physical space, including amphibians, reptiles, fish, and invertebrates, could be prioritized [182]. From an animal welfare perspective, these groups also present fewer challenges.

Various studies indicate that mammals are favored by the public [183], and references therein] but there is a growing greater representation of fish species diversity. The analysis of certain biological and geographical parameters shows that mammal and bird species in zoos are larger than their close relatives not held in zoos and that these captive taxa represent species with larger spatial ranges that are less likely to be endemic and are less likely to be threatened with extinction [184].

Approximately 95% or more animals are invertebrates, and if zoos were to represent this diversity proportionally, only 5% of their collections should comprise mammals, birds, reptiles, fish, and amphibians [176]. However, systematic groups such as insects or terrestrial snails only play a subordinate role, even if there are exceptions such as botanical gardens with butterflies as a very attractive group of insects [185]. The representation effort and success also differs within the main groups [186]. For example, almost all species of Cactaceae are shown in botanical gardens, while this is not the case within the two largest plant families Orchidaceae and Asteraceae [187]. The situation in vascular plants is comparable with the vertebrate species. The representation is biased. Some groups are almost fully represented, but whales, for example, cannot be adequately housed in aquaria [188,189].

Rare, endemic, and endangered species are now also being kept and propagated through conservation breeding programs in zoos and botanical gardens [190]. In this way, an increasingly important contribution to nature conservation can be made. At the same time, the attractiveness of the gardens increases. So it should be a win–win situation [191]. However, the options are limited. Endemic vertebrate species, vascular plant species, and other systematic groups are unlikely to be maintained in zoos and botanical gardens beyond individual conservation programs [192].

Interestingly, the role that zoos, aquaria, and botanic gardens play in endemic species conservation, versus simply anthropomorphically appealing species, is a little difficult to assess, and review studies are few in comparison with individual taxon-specific studies. We present below a brief overview of the role and success of endemic species conservation according to major taxonomic grouping by zoos, aquaria, and gardens.

Amphibians are the most threatened group of vertebrates, with over a third of extant species classified as "threatened" [193]. A global analysis of zoo and aquarium collections showed that only 2.78% of the collections comprised amphibian taxa, and this is both a challenge and an opportunity for zoos and aquaria to increase their capacity for the conservation of rare and threatened taxa [176]. Many zoos utilize amphibians for displays and education, without a conservation goal or strategy [194]. Amphibians are ideal for zoo-based research due to their small size, high fecundity, and ease of husbandry, and facilities for their breeding and maintenance are relatively cheap. In addition, amphibians are considered to be an excellent opportunity for conservation research partnerships [195]. Assessments of amphibian conservation breeding programs showed that species in breeding programs were likely to be under greater threat but had similar range-restricted distributions as those taxa not being bred for conservation purposes. Furthermore, amphibians in zoos seem to be as threatened as their close relatives not in living collections [196]. In addition, those species in zoos are generally larger bodied, more widely distributed, and more likely to be habitat generalists. These findings indicate that the ex situ conservation networks of zoos and other institutions are not prioritizing endemics as range-restricted habitat specialists with greater extinction risk. As an example, Madagascar has 370 native amphibian species, and amphibian endemism is extremely high, but a survey [197] found that a mere 36 of these species are kept in zoos globally. Of these 36 species, 10 are considered as "threatened", and the remaining species are not benefitting from any ex situ conservation actions. On a positive note, almost a third of those species in captivity have successfully reproduced [191].

Reptiles are quite well represented in zoos and aquaria [179]. However, we were not able to find general reviews of reptiles in zoological collections. As with amphibians and fish, there has, however, been a detailed analysis of the highly endemic Malagasy reptile fauna [193]. This fauna is rich, with 437 reptile species, of which 420 are endemic to Madagascar. Of these, only 87 are kept in zoos around the world, and the majority of these are species not considered to be threatened. However, what is perhaps encouraging for endemic Malagasy reptiles is the finding that almost 40% of their geographic range, on average, is within a protected area of some kind [198]. Reptiles, as with many other taxa, are also targeted by legal and illegal traders, and the consequences of this include escapes and subsequent invasions. Species traded are not generally endemic taxa and tend to be larger and more colorful or patterned species (e.g., [199]). Reptiles in zoos are also larger-bodied species, and endangered species, which may not be visually attractive to humans, do not feature extensively in zoo collections, a fact that cannot be explained by the difficulty of obtaining rare species [178].

The preference for larger and more colorful birds is also evident in zoo collections. Eight percent of the world's threatened bird species are kept in captivity [185], and zoos tend to favor birds that are not endemic or threatened [180]. Additionally, there is an indication that the average diversity of bird species in zoos declined between 1960 and 2018 [200]. As with other taxa, Madagascar is a hot spot of bird diversity, and 142 out of the 195 bird species on Madagascar are endemic, 28 of which are threatened [190]. A survey of 131 institutions indicated that only 15 of these endemic species were kept in their living collections, meaning that 89% of Malagasy birds are not represented in ex situ collections. It thus appears that zoos do not have a strong track record of ex situ conservation of endemic birds, but given the global plethora of conservation organizations with a strong focus on birds, perhaps this role is not considered a key strategy for zoos.

Freshwater fish species compose approximately 25% of all vertebrate diversity, and freshwater fish compose about 50% of all fish diversity [201]. The majority of freshwater fish species lack any formal IUCN Red List status. However, holdings of fish in zoos and aquaria increased between 1960 and 2018 [197]. Aquaria and zoos only hold about 7% of all threatened fishes, and this highlights the important role that hobbyists play in the conservation and breeding of endemic and threatened taxa [202]. Hobbyists make up 99% of the global ornamental fish trade and may play a vital role in fish conservation. This role has been facilitated by the formation of the CARES (Conservation, Awareness, Recognition, Encouragement, and Support) preservation program in 2004. CARES has published a priority list which contains nearly six hundred species (24 of which are extinct in the wild) from twenty families. Notably, species from Tanzania and Mexico, which are major centers of fish diversity and endemism, had the greatest representation in this list. However, the legal (and illegal) trade in endemic freshwater fishes for the hobbyist market can also be highly detrimental to conservation efforts [203]. Another freshwater fish hot spot for endemism is Madagascar, which has 173 fish species, 79 of which are endemic. These face extinction due to deforestation, overfishing, and the introduction of exotic species. However, only 21 of these species including 19 endemics are kept in zoos, with some success of ex situ breeding [204].

Being small and generally inconspicuous, invertebrates tend not to feature highly on the agendas of zoos and aquaria [205]. In 1991, one successful international invertebrate captive breeding program was reported [206], but by 1994, a growing public interest in, and value of, invertebrate collections in zoos was being recognized [207], and zoos embarked on invertebrate conservation (e.g., [208,209]). Butterflies are considered to be flagship taxa, and there has been a rapid increase in "butterfly houses" at zoos and in tropical houses of botanical gardens, but there are a number of risks to butterfly biodiversity linked to this "industry" [210].

As with zoos, humans have cultivated plants in gardens since ancient civilizations, notably for the cultivation of medicinal plants, exotic fruits, and spices [211] The focus on "physic gardens" in the 1500s in Europe set the scene for the subsequent growth of gardens as a consequence of the era of exploration and European colonization. These gardens facilitated the rise of taxonomy, and the economic value of selected species such as coffee, rubber, tea, cotton, opium, sugarcane, etc. is linked to societal evils such as slavery and warfare (e.g., [212,213]). There are over 3000 botanic gardens worldwide, but as with the global distribution of zoos, two-thirds of these are located far away from the world's 36 biodiversity hot spots (Figure 2 in [211]). Despite this, botanic gardens and arboreta grow at least one-third of all known vascular plant species. Of these, over 16,000 are tree species, of which 1700 are globally threatened [214]. More recently, the role of botanic gardens in researching and conserving plants in the face of climate change studies and food security have become increasing priorities [215–217]. However, the space required in gardens to grow trees means that only a limited number of species and individuals can be accommodated. There is thus a specific role for arboreta in the conservation of tree species. In South Africa, for example, there are currently 121 arboreta. Historically, there were at least 172, but many have been lost. The origins of some of these are linked to the rise of the forestry industry and the need for research on suitable tree species. These arboreta house 2309 species from around the world, of which 128 species are threatened [218]. In recent times, activities and strategies of botanic gardens worldwide are guided by the Botanic Gardens Conservation International [BGCI] *Manual on Planning, Developing and Managing Botanic Gardens*. The BGCI was founded in 1987. It was this organization that drove the rise of plant conservation activities at botanic gardens [219–222]. However, gardens cannot readily grow sufficient number of individuals so as to ensure the maintenance of genetic diversity, and the potential for genetic erosion exists [223,224]. Even the role of seed banks in maintaining genetically diverse collections is limited. However, seed banks are able to store many more species than living collections in gardens. There are over 350 botanic gardens involved in seed banking in 74 countries [225]. According to this survey, 56,987 taxa have been banked as seed, 9000 of which are threatened. In the context of the space requirements for trees, tree seed banking is an obvious solution, and seeds of 6881 tree species (half of which are endemics) from 166 countries are stored in seed banks [226]. However, these authors make a call for even more effort to collect and store seeds of threatened species.

7. Conclusions and Outlook: What Are The Perspectives for Endemics and Centers of Endemism?

The main goal of nature conservation programs according to the aspiration of the Convention on Biological Diversity (CBD) is survival and evolution of biological diversity in its entirety, i.e., well-being of all species on Earth. Since endemism is a precondition of extinction, the focus on the survival of endemics and CoEs is essential.

Endemism and endangered species are closely coupled, and different kinds of threats cause different impacts and risks of extinction [227]. According to the IUCN Red List, land use, land use change, and intensification of use has a much stronger impact on ecological conditions for most critically endangered species than, e.g., climate change. Cities, urban habitats, and arable land with prevailing unfavorable conditions for the survival of threatened endemics are continuously growing, while natural and semi-natural habitats harboring large numbers of endemics are declining in quantity and quality. Anthropogenic influences, change and intensification of land use activities, conversion of whole ecosystems, the application of agrochemicals, the growth of arable land and urban environments, and the use of biological resources have the strongest impact and cause the greatest risk for the existence of populations and survival of threatened endemics [228–231]. Climate change, including severe weather, is less important but has a stronger impact than, e.g., natural processes such as tsunamis, volcanism, or landslides [232–236].

Vascular plants and vertebrates are by far the most important groups conserved in zoos, aquaria, and botanical gardens. Nevertheless, most species on Earth are invertebrates, and most of them are not scientifically described. Little is known about their ecological requirements and specific environmental problems. With the exception of certain groups of vascular plants, vertebrates, and a few other groups of organisms, most taxa and their ecology have not yet been adequately studied. This knowledge deficit should be seriously considered when ecosystems, landscapes, and regions are economically used and ecological conditions are impacted by anthropogenic activities [231,237,238].

If continuity of environmental conditions is the best predictor for survival of endemics, many of them threatened with extinction, then avoidance of intensification of use and change of conditions at landscape scales would simply stabilize the conditions of their existence. Avoidance of land use and land cover change at landscape scales can be seen as the most important precondition for ecosystem functioning and survival of biodiversity, even if this is not guaranteed. This is even more important since humankind obviously is not able to limit climate change in the coming years and decades. Even with avoidance of land use changes, climate change is impacting rare species and increasing the risk of extinctions.

Thus, the limitation of direct anthropogenic influences at landscape scales, wherever possible, should have highest priority for maintaining ecosystem functioning, survival of endemics, and provision of adequate ecological conditions. Because CoEs harbor high numbers of endemics, monitoring of these areas can seriously contribute to effective nature conservation management with a focus on biodiversity conservation.

The importance of zoos, aquaria, and botanical gardens with respect to nature conservation is increasing. However, the distribution of the world's zoos and botanic gardens in general represents great distances from the world's CoEs. Botanic gardens are more effective at the conservation of endemics, but zoos face far greater challenges in this regard, having to balance the demands of the public, wishing to see iconic, larger species on one hand with dedicated conservation projects on threatened taxa. In addition, zoos have space limitations and animal welfare including behavior considerations that limit their ability to house large numbers of endemic species. The representation of different groups of taxa is biased; e.g., amphibians compared with invertebrates have a more globally coordinated conservation approach than others. Holdings of endemic invertebrates in zoos and other facilities need to be increased. Seed banking of plants is clearly space-efficient, but ensuring sufficient genetic diversity is essential. There is an obvious role for seed banks and botanic gardens in addressing food security challenges, especially in terms of crop wild relatives and indigenous food plants used by peoples around the world.

Ecosystem functions of species-rich and species-poor ecoregions and CoEs are directly linked with social aspects including human aesthetics, well-being, health, ecology, and economy. Nevertheless, this is an open field with many questions that science has to answer in the future. As a first step, it might be helpful to intensify the communication between ecologists, social scientists, and conservation practitioners in botanical gardens and zoos [239–243]. A systematic analysis and information network of the quantitative and qualitative participation of ex situ conservation in zoos, aquaria, and botanical gardens might be a topic for further research on relationships including regional endemism and CoEs. Meaningful long-term partnerships in endemic species conservation between institutions in countries in the global north and the biodiverse rich and often developing world need to be strongly encouraged, and the "parachute science" approach needs to be discouraged [244,245] if there is to be a meaningful increase in the ex situ conservation of endemic and rare taxa from these regions of endemism.

Author Contributions: Conceptualization and first draft preparation, C.H.; discussion of all parts of the manuscript, C.H. and N.B.; collation of the section about zoos and botanical gardens, N.B.; tables and visualization of figures, C.H. All authors have read and agreed to the published version of the manuscript.

Funding: No external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Not applicable.

Acknowledgments: We thank Laura Sutcliffe and Merel Herdeg for helpful comments, for support with the design of illustrations, and for correcting the manuscript.

Conflicts of Interest: The authors declare no conflict of interest.

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