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Twenty years of biodiversity research and nature conservation in the Socotra Archipelago (Yemen)

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The topical collection 'Twenty years of biodiversity research and nature conservation in the Socotra Archipelago', in short 'Socotra biodiversity research and nature conservation' was conceived at the 18th Friends of Socotra annual meeting and Socotra conference which took place at the Orto Botanico di Palermo, Palermo, Italy, 26–29 September, 2019. In total, 13 research papers are included in the collection, which covers a selection of the latest scientific progress on the fauna and flora of the terrestrial and aquatic environments of the Socotra Archipelago UNESCO World Heritage Site (Yemen). Topics include conservation, taxonomy, ecology, biology and biogeography. The focus is mainly on biodiversity conservation and aimed at identifying current challenges, trends and processes that may impact on local ecosystems and livelihoods, based on analysis of data collected over the last decades. With this collection, we wish to emphasise the importance of taking into account science-based conservation approaches in future strategic steps towards safeguarding the ecosystems of Socotra.

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1 Background

For centuries, islands and their biotas have appealed to biologists. Covering only 5% of the Earth's land surface, these 'living laboratories of evolution' account for a high proportion of endemics—about 20% of all known vascular plants and 15% of all amphibians, mammals and birds are found exclusively on islands (Da Fonseca et al. 2006). However, due to several factors that are typical to insular ecosystems such as isolation and small sizes of local populations, overwhelming evidence has shown that species on islands are easily driven to extinction. General factors are well known and include the effects of exotic species, habitat degradation and deliberate destruction (Sax and Gaines 2008; Caujapé-Castells et al. 2010; Wood et al. 2017). Therefore, in conservation efforts, approaches for islands must be very different to those in the continent (Whittaker 1998). The rich biodiversity of the Socotra archipelago forms no exception to the brutal mathematical reality of how rapidly extinction occurs on islands.

The Socotra Archipelago is situated in the western Indian Ocean near the Horn of Africa and belongs to Yemen. It consists of a few islands of which Socotra is the largest (Fig. 1), the latter covering a land area of about 3600 km^2. Ever since the first scientific expeditions to Socotra towards the end of the nineteenth century, biologists have been fascinated by this place with its strange umbrella- and bottle-shaped trees. Most likely, Charles Darwin would have loved visiting the 'Galápagos of the Indian Ocean' instead of the Ecuadorian islands; however, strong monsoons used to cut Socotra off from the world for about half a year and therefore opportunities for research were few. Only in the last 50 years has Socotra been more accessible to researchers, in particular since the establishment of an airstrip and an increase in traffic and immigration over the last two decades (Van Damme and Banfield 2011). The turn of the last millennium is also the period when major conservation programmes started on

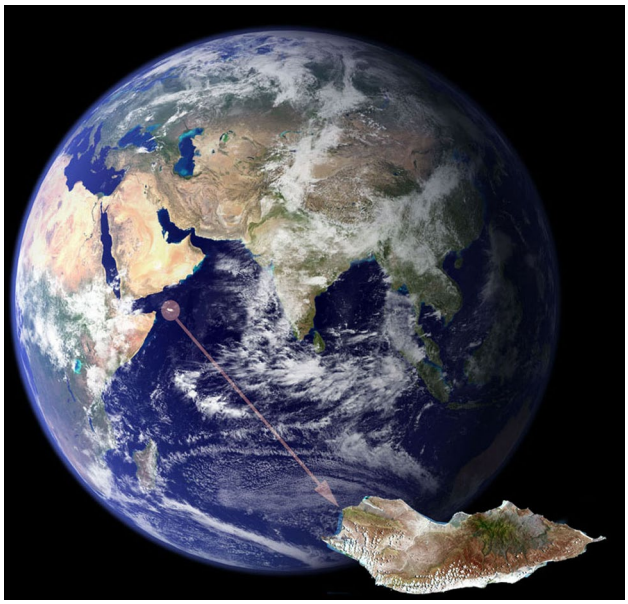

Fig. 1 Socotra Island is part of a small yet significant Yemeni archipelago, situated in the western Indian Ocean just off the Horn of Africa. It is the largest island of Arabia. Since 2008, the Socotra Archipelago has been listed as one of Yemen's UNESCO World Heritage Sites, in particular for its rich biodiversity and high number of endemic species. Image from Google Earth, modified by Kay Van Damme

the islands, which in 2008 received recognition as UNESCO World Heritage Site, based purely on the criterion of harbouring globally important biodiversity and a high proportion of endemics (Natural WH Site).

About two decades ago, when the most recent episode of research in Socotra had just started, a charity by the name Friends of Socotra (FoS) was established. The non-governmental, non-profit organisation consists of predominantly researchers and provides a multidisciplinary and politically neutral platform for discussion, interaction and synergies related to the conservation of the unique biodiversity and culture of these Yemeni islands. Through annual conferences, a newsletter and small awareness or pilot activities on the ground together with other organisations and local NGOs, FoS (www.friendsofsoqotra.org) is the only organisation of its kind that focuses on scientific efforts related to the unique cultural and natural heritage of the Socotra Archipelago. The organisation is unusual, as few islands or island groups in the world have an international, multidisciplinary group of scientists investing voluntary time in promoting awareness for local science and conservation. The group is driven entirely by the enormous efforts by former and current volunteers from all over the world who have supported the organisation in the past two decades, and who have a heart for Socotra.

2 The topical collection

The topical collection 'Socotra Biodiversity Research and Nature Conservation' materialised as a result of the important synergies that are generated at the Friends of Socotra meetings. In the last two conferences, which took place in the Kingdom of Bahrain and in the Botanic Garden of Palermo in Sicily, respectively, we proposed a topical collection which crystallised into the current output. Representatives from Yemen were present, and several Socotran conservationists scientifically contributed to the meetings and to the papers in this collection. At the Palermo meeting (Van Damme and Livadiotti 2020), an important awareness activity focusing on Socotra biodiversity was launched, the UNESCO-FoS campaign entitled Connect-2Socotra which took place in different scientific institutes around the world (https://en.unesco.org/connect2socotra).

The topical collection focuses on 20 years of biodiversity research and conservation of the terrestrial environment of the Socotra Archipelago UNESCO World Heritage Site. The reasoning behind this collection is to provide the scientific data and approaches to conservation and to evaluate what can be learned from assessing the environmental information that was gathered through international collaborations in recent years. The collection focuses on trends through the analysis of decades of data and includes completely new observations as well as introducing new techniques that can locally be used for biodiversity monitoring. Several studies in this topical collection result from years of continued data acquisition under difficult field conditions in close coordination with local authorities and conservationists, with full support by the Ministry of Water and Environment and the Environmental Protection Agency (EPA) of Yemen and EPA Socotra Branch, to whom we are very grateful. The interaction between conservationists from different cultures working on a common goal over many years, continuing essential scientific work for biodiversity during a time of hardship and war in Yemen, has led to fruitful collaborations.

Studies that examine actual changes in the Socotran ecosystems over time are few (Van Damme and Banfield 2011; Maděra et al. 2019). Nevertheless, such studies are crucial to assess imminent extinction risks and to strategise proposed solutions. The main threats to the terrestrial environment are well known (Van Damme and Banfield 2011) and have been highlighted since years by the World Heritage Committee for Socotra. The IUCN Conservation Outlook (2017) has put the digit at an alarming 'Significant Concern' for Socotra. This topical collection also serves the purpose of a warning by the scientific community: as shown here, there are clearly processes on Socotra that can lead to imminent extinctions. And the

Fig. 2 Overmature stands of one of the archipelago's unique and endangered frankincense tree species (*Boswellia elongata*) in an overgrazed Socotran landscape before (left) and after (right) damage caused by climate change (cyclones in 2015). Photos from Homhil Nature Sanctuary, eastern Socotra Island, by Kay Van Damme (May 2010) and Petr Maděra (2016)

extinction of a single individual or a small population, whether it belongs to a species of plants or animals, matters. For example, the loss of a single individual of the iconic Socotra Dragon's Blood Tree (*Dracaena cinnabari*) would not only affect the entire vegetation that lives sheltered below the canopy and the animals associated with it (Rejžek et al. 2016; Vasconcelos et al. 2020), but it may also change the amount of water that is part of the island's hydrological cycle on which human life depends (Kalivodová et al. 2020). Often, effects that we see today are the results of trends that have been set in motion over the last decades, and which are accelerated through global warming and other, more direct, human interventions.

This is the case for the frankincense tree *Boswellia elongata* (Fig. 3) which is one of the most important endemic plant species in Socotra. Not only is the most typical Socotra frankincense tree endangered, but it also plays a key role in the island's culture and has potential benefit for economy, as perhaps it did in a distant past. A close study of individual trees from aerial photographs now provides the first direct visual evidence of this species' decline and indicates the imminent extinction of its largest subpopulation. Researchers witnessed a clear reduction in the largest subpopulation of *Boswellia elongata* on Socotra Island between 1956 and 2017, a period of 61 years, by about 78% (Lvončík et al. 2020). Through experimental designs and assessment of the potential causes, the decline has been attributed to both natural and human-mediated factors. Senescence of the tree stands and decades of overgrazing by goats (now roaming more freely because of a shift in culture, i.e. use

Fig. 3 The analysis of data that has been collected over decades, now provides an objective view on how the immune system of Socotra's terrestrial environment, on which local people depend, is compromised. Strategic efforts to increase local resilience of plant and animal populations are vital to ensure that future generations can benefit from the ecosystem services of the iconic species that have made the island so famous. The Socotra Dragon's Blood Tree, for example, does not only harbour a wide range of endemic species, it also plays a role in the island's hydrological cycle. Photo by Kay Van Damme, Socotra Island, 2014

of the rangeland), have made natural regeneration of most ground-dwelling palatable plants in accessible areas nearly impossible, in particular in times of drought when grazing pressures intensify (Miller and Morris 2004; Lvončík et al. 2020). The process is catalysed by non-selective overarching events such as climate change, which could potentially give the final nudge for Socotran species that are on the edge at the downward slope towards extinction (Van Damme and Banfield 2011).

Global warming recently manifested itself in Socotra in the form of extreme weather events (cyclones and torrential rains) which have caused damage to the terrestrial environment. Physical destruction to the frankincense trees caused by unusually strong winds could be clearly attributed to two cyclones in 2015 and are accountable for more than a third of the individual trees that have disappeared in one of the island's largest populations (Fig. 2). Weakened by the combination of overgrazing and damage by wind, the population was attacked by a local species of bark beetles on top of that. If the trend continues, the iconic subpopulation of frankincense trees in a well-known protected area on the island (Homhil Nature Sanctuary) will be gone in only a few decades from now (Lvončík et al. 2020). The events are not localised; we may expect that the majority of exposed areas where this and other endemic ground-dwelling tree species occur on the island are facing a similar situation. The rate of extinction is specific to biological attributes of the species, however, studies show similar trends for other endemics, like *Dracaena cinnabari*, albeit over centuries rather than decades (Maděra et al. 2019). First estimates of age indicate that many trees of the latter species can easily be several centuries old (Maděra et al. 2020). In some species, relatively less palatable to goats, regeneration is good, such as in the endemic *Dendrosicyos socotranus*, Socotra's famous cucumber tree. Habrová et al. (2020) found regeneration for this species in 77% of the locations studied. However, to avoid an entirely skewed landscape that is mainly dominated by grazing-tolerant species, efforts are needed because ground-rooting species are truly at risk. The grazing impacts on vegetation is stronger during dry periods when there is less choice for alternatives, as exclosure experiments show (Lvoncik et al. 2020).

Ecosystems dominated by trees in the Socotran landscape are not as widespread as it would appear to the outside. Satellite image analysis using available state-of-the-art approaches combined with ground-trouthing indicates that the Socotra highlands and mountains harbour the majority of the trees (Riccardi et al. 2020). Statistical analysis suggests that the overall distribution of trees on the island is still largely governed by natural factors such as soil availability and local climate, less so by direct human impacts. For now. As the population grows, these impacts may increase further as well. Such impacts can be monitored also using remote sensing technologies. Vegetation productivity in Socotra was assessed over ca. 20 years using NVDI (normalised difference vegetation index) (Rezende et al. 2020). The results show that overall the island seems very dynamic in terms of vegetation productivity, however the mountain areas and wadi slopes show a clear decrease over the past decades and in particular over the last few years (Rezende et al. 2020). The decrease could be attributed to the long-term effects of grazing combined with the effects of extreme weather events, leading the loss of vegetation, as in the *Boswellia* case study, and the loss of soil linked to erosion.

Plants are also important for many endemic vertebrate species on the island, such as birds and reptiles that are strongly dependent to the availability of healthy stands of woody vegetation. About 90% of the terrestrial reptiles are endemic to the archipelago, and several of those rely on the availability of the trunks and branches of trees or bushes (Fasola et al. 2020). The endemic gecko *Hemidactylus dracaenacolus*, assessed as critically endangered in the IUCN Red List, is even found exclusively on tree trunks of the endemic Dragon's Blood Tree (Vasconcelos et al. 2020). Therefore, the declines or the disappearance of vegetation through a combination of factors, may accelerate the direct extinction of associated species in the absence of vegetation cover. Considering the rapid changes in vegetation over the last decades (Lvoncik et al. 2020; Rezende et al. 2020), the fact that some endemic reptiles have a total area of occupation of less than 10 km^2 (Fasola et al. 2020) and the presence of invasives such as rats and cats, extinction scenarios for these island endemics are realistic if there is no direct intervention.

On an island, everything is closely connected, and so are people to their environment. The vegetation does not only play a key role in creating niches for other plant and animal species, but also may provide another important ecosystem service as part of the hydrological cycle of the island. Kalivodová et al. (2020) measured the amount of horizontal precipitation caught by individual Dragon's Blood Trees. The authors estimated that at the highest altitudes (ca. 950–1550 m a.s.l.), the mean annual horizontal precipitation below the tree crown is about 790 mm, exceeding 40% of the total annual precipitation. Considering the relatively slow growth of Dragon's Blood Trees (Maděra et al. 2020), conservation strategies to preserve these assets will need local involvement for the duration of more than a human lifetime.

The freshwater environments also show a decline in indicator species. A first analysis of 123 years of dragonfly records in the archipelago suggests a decline in the relative richness of these conspicuous insects in the area of the coastal capital of Socotra, Hadiboh (Van Damme et al. 2020). Although species richness in this animal group is not high, the pattern is clear and it affects several species. The latter is relevant to the protection of local wadis, but

particularly shows the need to protect coastal lagoons, which harbour a rich diversity of birds, fish and arthropods. A conspicuous dragonfly called the phantom flutterer (*Rhyothemis semihyalina*), disappeared from Socotra's coastal lagoons in the east and the west. Even though the latter study is not based on standardised surveys, it is the first long-term study assessing changes over time in animal species richness on Socotra. In this case the decline was attributed primarily to habitat alteration through urban development. The study shows also that there is a cultural dimension to these insects locally—the people of Socotra recognise dragonflies as a sign of good water and they have no less than six terms in the unique language to describe them. Such positive interaction towards invertebrates can be a very valuable asset in local conservation, for example to protect the iconic beautiful Socotra bluet (*Azuragrion granti*), the archipelago's only endemic damselfly, Near Threatened in the IUCN Red List (Van Damme et al. 2020).

The above, habitat degradation and climate change, are all well-known factors that impact on biotas worldwide. However, arguably the worst known drivers of extinctions on islands are the invasive alien species. Exotic species are a well-known threat to biodiversity on Socotra, but the arrival of new and unwanted guests may strongly impact on local economy and culture as well. Witt et al. (2020) present the first records of detrimental plant pests, the red palm weevil (*Rhynchophorus ferrugineus*) and the dubas bug (*Ommatissus lybicus*) on Socotra, two invasive alien species which are known to strongly reduce date palm yields in the region. Another new invasive on Socotra is recorded in Hula and Niedobová (2020), the Mediterranean recluse spider, of which the bite can pose a risk to children. Based on successful eradication programmes in other places in the world, Witt et al. (2020) suggest that more measures are urgently needed to protect the island and its biodiversity and livelihoods, from exotics. Such measures would include phytosanitary approaches, quarantine facilities at the port and airport, and most importantly a good communication between all stakeholders to mutually arrive to the best strategies (Witt et al. 2020). Even though such suggestions have been made repeatedly in recent years and despite efforts as part of ongoing projects, and a priority issue as identified by the World Heritage Committee, such measures were unfortunately never achieved on the ground. However, the delays in implementation increase the risk of more pest incursions as evident in the presence of the red palm weevil and other invasive alien species. Therefore, such exotics pose huge risks, not only towards the unique biodiversity of Socotra, but also for local livelihoods, the unique culture and human health. More invasives may be present on the island yet remain undetected.

Despite the challenges, Socotra is still at this moment, a treasure trove of biodiversity. While freshwater environments are largely well studied, the terrestrial environments still harbour new species that rest in existing collections. For example, new species are being described from collections from the first large (among the recent biological) expeditions, now 20 years ago. People who describe species in animal and plant groups are part of an endangered population themselves; however they keep carrying out this important and tedious taxonomical work. In this topical collection, malacologists Neubert and Bochud (2020) describe two new endemic species of molluscs from the terrestrial environments of Socotra. Also, in the flora of Socotra, still a large amount of work remains to be done, in particular in assessing the genetic diversity of plant populations that may or may not harbour cryptic species, although much more research is needed for single species (Giovino et al. 2020). All these taxonomical works can help to understand patterns of diversity, areas of higher richness, and help to even look into biogeographical patterns of richness and evolution, as Purchart et al. (2020) have started for butterflies, darkling beetles and spiders in the archipelago. Comparing such patterns in diversity and comparison to other islands can be key to global research in biodiversity and biogeography.

3 Outlook

As the publications in this topical collection contribute to our knowledge of the terrestrial and aquatic environments in the Socotra archipelago, they thereby may help to identify the challenges that other fragile insular ecosystems and arid lands in the world face. These challenges are global and have been identified on Socotra years ago, before the effects were as visible as now. It is clear from the studies herein that if the current trend continues, the Socotran ecosystems may actually rapidly lose iconic endangered species and a perhaps equally fragile endemic culture over the next decades or centuries (Fig. 3). This trend is realistic and should be met with matching efforts in conservation.

Socotra has changed. The changes in the terrestrial ecosystems now have become tangible and seem to manifest themselves clearly when examining processes over a few decades. Such processes can only be observed through rigorous scientific approaches and targeted monitoring, covering years of data. Such research, which only started at the turn of the millennium in Socotra, is vital to strategise conservation priorities, while practical activities are needed to focus on applied science that assesses positive effects from interventions. Primarily environmental factors, more than human factors, seem to currently drive the dynamics of the terrestrial ecosystems in Socotra, sometimes in pulses of increased intensity, and these effects likely will continue to catalyse changes on the islands and its inhabitants in the years to come. Climate change impacts have also clearly

revealed the sensitivity of local endemic plant species, which will need to retain a strong resilience and positive human interventions to avoid extinction. However, the new studies in this topical collection reveal that not only climate change, but also cultural and socio-economic effects play a role in affecting the landscapes, albeit through perhaps slower and sometimes more localised processes. These include effects of (i) overgrazing, leading for example to overmature tree populations of palatable species, (ii) urbanisation, altering coastal areas including lagoons and wadis, and (iii) new invasive alien species which are more likely to arrive now due to an increase of import and lack of control measures at entry pathways, and which may have a devastating effect, not only on biodiversity, but also on food security and local livelihoods. The combined effect of overgrazing and climate impacts, seem to also lead to loss of vegetation in the mountains, Socotra's local biodiversity hotspot. Even though we have an image of the Socotran people as being stewards of their environment for centuries (Van Damme and Banfield 2011), new challenges arise and cultural shifts have been disrupting the bond between people and their environment since decades, as is evident in the overgrazing effects. The local capacity to cope can benefit from strategic and cost-effective solutions, which can be helped by science.

The immune system of Socotra is now compromised. The current status of the ecosystems is unravelled by impacts that painstakingly reveal slower underlying mechanisms. Extinction is a relatively slow process; however as it is known to be accelerated strongly in island biotas, we may soon be running out of time to protect Socotra's most iconic flagship species and the biota associated with them. The causes and pathways for extinction are well known, and if not countered by immediate strategic conservation action involving local communities, several typical species will clearly not survive the coming centuries. If the trend continues, future generations might be able to visit a Socotran frankincense tree only in a botanical garden, accompanied by a little plaque saying 'extinct in the wild'.

We believe there is time to turn the tide. Human impacts on nature can be reduced as shown in other places in the world. It needs all crew aboard working together and some positive currents to avoid a ship from crashing. In order for the ecosystems to be resilient in the face of upcoming challenges, it will require all hands on deck. Science-based strategies, cooperation and community involvement are key and have shown to be effective in other highly valuable biodiversity areas in the world.

As Socotra is recognised by UNESCO as a Natural World Heritage Site, there is a large interest in supporting the local environment, materialised in several ongoing conservation projects. If such efforts are managed properly and in full support of the local authorities and local communities to help against the coming challenges, major challenges can be faced. Improved biosecurity measures are an example of cost-effective priority measures to avoid loss of future local livelihoods and biodiversity, and to avoid more costly future interventions to eradicate invasives. To keep promoting the communication of scientific outputs towards a wider public, providing science-based options to conservation, and to keep spreading awareness about the island's uniqueness, an organisation like FoS and collaboration with local environmentalists and authorities are key. The latter is illustrated by the fact that no less than five papers in this topical collection include indigenous co-authors from Socotra Island.

We hope that these scientific contributions related to conservation science in Socotra, presented in this topical collection, can help to strategise future activities and help reverse some adverse impacts from climate change and other processes that drive species to extinction.

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