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ABSTRACT

African freshwater ecosystems are increasingly being impacted by humans, requiring an effective tool to assess these impacts for future conservation action. Such a tool, the Dragonfly Biotic Index (DBI), was earlier developed to assess the quality of South Africa's freshwater ecosystems and is based on combining the scores of three sub-indices (geographical distribution, threat status, and habitat sensitivity) for each South African dragonfly species. The sum of the DBI scores for all the species recorded at assessed sites indicates the relative quality of these sites. The International Union for the Conservation of Nature/Species Survival Commission (IUCN/SSC) has assessed the threat status of certain aquatic taxa in Africa, including dragonflies. These assessments, coupled with the latest information on the geographical distribution of each species, makes it possible here to geographically expand the South African DBI into a continental-scale assessment index (the African Dragonfly Biotic Index (ADBI)) by adapting the South African DBI sub-indices. We develop this continental index here. However, there are challenges when undertaking an assessment at the continental scale compared to a national scale. In particular, the habitat sensitivity sub-index of the South African DBI is a relative, quantitative measure based on numbers of individual dragonflies recorded from natural versus human-modified or artificial freshwater systems. While the data for the two sub-indices, species' geographical distribution and Red List threat statuses, are available across the continent, this is not the case for the habitat sensitivity sub-index at this large spatial scale. This meant that an alternative sub-index measure was required. We overcame this challenge by exploring an alternative sub-index, i.e. the 'species vulnerability sub-index', based on knowledge of the vulnerabilities of the species to certain types of landscape transformation. Then, the species vulnerability sub-index scores were calculated and combined with the geographical distribution and Red List threat status sub-index scores to develop ADBI scores for a core of 604 dragonfly species with adequate data across the African continent. These ADBI scores provide a workable framework and baseline for determining freshwater quality, both lotic and lentic, relative to human disturbance at a continental spatial scale. The ADBI enables the monitoring of quality changes, for better or worse, over the continent in years to come. Overall, the ADBI also has the potential to help identify threats to, and sensitivities of, African freshwater ecosystems, leading to conservation action.

1. Introduction

Freshwater ecosystems are being increasingly impacted by adverse human activities (Malmqvist and Rundle, 2002; Dudgeon et al., 2006; Vörösmarty et al., 2010; Carpenter et al., 2011). In Africa, with its highly unpredictable climate, combined with one of the fastest growing human populations, makes its freshwater ecosystems particularly vulnerable (Shumway, 1999; UNEP, 2002; Thieme et al., 2005; Darwall

Abbreviations: ADBI, African Dragonfly Biotic Index; ADHM, African Dragonfly Habitat Matrix; DBI, Dragonfly Biotic Index (South Africa); IUCN/SSC, International Union for the Conservation of Nature/Species Survival Commission; ODA, Odonata Database of Africa

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et al., 2011). Therefore, it is essential to identify possible aquatic diversity that may be at risk, as well as important biodiversity areas for future conservation action. This can be accomplished with assessment tools based on effective indicators of freshwater condition that are applicable over a wide geographical scale and wide variety of freshwater types. It also needs to be understood by non-specialists to be useful as a practical tool.

South Africa has already paved the way, through the development of two freshwater monitoring methods based on indicators that assess the ecological state of its freshwater ecosystems: the South African Scoring System (SASS) and the South African Dragonfly Biotic Index (DBI). SASS was developed to assess the health of southern Africa's rivers by using easily recognizable benthic macroinvertebrate groups (Dickens and Graham, 2002). However, it has some shortcomings, such as being only of value in running waters and uses only higher taxonomic levels, rather than at the more sensitive species level (Simaika and Samways, 2011). It also requires the evaluator to wade into the water, which is potentially hazardous through exposure to dangerous pathogens and vertebrates (Dickens and Graham, 2002; Samways and Simaika, 2016).

A prototype of the Dragonfly Biotic Index (DBI) was introduced by Samways and Taylor (2004), and further developed by Simaika and Samways (2009, 2011, 2012), leading to a practical manual for its use in rapid assessment of South Africa's freshwater ecosystems, both lentic and lotic (Samways and Simaika, 2016). This tool is based mainly, but not exclusively (i.e. larvae and exuviae can also be included) on the presence of adult dragonfly species (Anisoptera and Zygoptera) at any one site. Dragonfly assemblages are widely recognized as effective indicators of environmental health in freshwater ecosystems (Clark and Samways, 1996; Chovanec, 2000; Smith et al., 2007; Dutra and De Marco, 2015; de Oliveira-Junior et al., 2015; Golfieri et al., 2016; Valente-Neto, et al. 2016) as they are bright, colorful, conspicuous and well-known insects (Kalkman et al., 2008), making them effective for assessing freshwater bodies and their surrounding water margins according to the health and ecological integrity of these water bodies (Samways, 2005; Smith et al., 2007; Oertli, 2008; de Silva et al., 2010; Simaika and Samways, 2011; Kutcher and Bried, 2014; Golfieri et al., 2016; Martín and Maynou, 2016; Valente-Neto et al., 2016). Their effectiveness comes about from their assemblages being sensitive to both changing landscape and biotope structure and condition (Samways and Sharratt, 2010; Goertzen and Suhling, 2019), as well as in-water conditions (Kietzka et al., 2017).

Dragonflies are also highly mobile, and can rapidly respond to changing environmental conditions, either by moving towards them when favorable or away from them when not (Samways and Simaika, 2016). In short, a certain suite of dragonfly species recorded at a site defines the ecological integrity of that site according to the traits of the particular species. In turn, the overall assemblage composition is indicative of the extent to which a freshwater ecosystem and its surrounds has moved away from the historic reference condition, either negatively, or positively in the case of restoration (e.g. Samways and Taylor, 2004; Samways and Sharratt, 2010). The effectiveness of the DBI lies in magnifying the difference between, on one hand, species that are geographically widespread, not threatened, and tolerant of human disturbed ecosystems, and on the other hand, those that are geographically restricted, threatened with extinction, and highly intolerant of human disturbances to their habitats.

Each species has a particular DBI value, and this value is derived from the total of three sub-indices: 1) the species' geographical distribution, 2) the International Union for the Conservation of Nature/Species Survival Commission (IUCN/SSC) Red List threat status, and 3) the sensitivity of each species to human disturbances to their habitats. The scores of each of these DBI sub-indices range from 0 to 3, with the final DBI value of each species being the sum of scores for the three sub-indices, which ranges from 0 to 9. In other words, a dragonfly species that has a widespread distribution, is non-threatened, and is highly tolerant of human disturbances scores 0 (0 + 0 + 0), whereas a species that has a highly restricted distribution, is highly threatened, and is extremely sensitive to habitat disturbances scores 9 (3 + 3 + 3). A description of these three sub-indices, as they are classified and scored, is given in Appendix A (Supplementary material), taken from Samways and Simaika (2016).

The sum total of all the species' scores at a site either decreases (from loss of the high-scoring species, but maintenance of low-scoring species) when conditions are deteriorating, or alternatively, the total increases (through return of high-scoring species in particular) when conditions improve. In other words, a DBI/Site value (total DBI scores for a site divided by the total number of species recorded at the site) is calculated, which can be used to compare different sites, or even the same site over time (i.e. the ecological integrity of one site is considered the same as that of another where the same set of species is recorded) (Samways and Simaika, 2016). Consequently, the conservation status of certain freshwater ecosystems (i.e. lentic and lotic) can be assessed over both space and time.

Africa's aquatic fauna is poorly understood (Dudgeon et al., 2011), leading to the IUCN/SSC gathering a database on water conditions and biodiversity of certain aquatic taxa (i.e. fish, freshwater molluscs, dragonflies, crabs and aquatic plants) occurring in the freshwater ecosystems across the African mainland (Darwall et al., 2011). However, these data have not yet been transformed into practical tools that can be used to monitor the changing conditions of the freshwater ecosystems. Besides having a practical indicator that can be used to monitor the health of these ecosystems, the ecological sensitivity and possible vulnerability of particular indicator species needs to be known for the tool to be applicable. However, the African continent as a whole is lacking an assessment tool that can rapidly assess changing conditions of its freshwater ecosystems. Therefore, the main aim here is to create an assessment tool for the rapid assessment of all types of freshwater ecosystems across the African continent. As there were data available on African dragonfly species distributions and their Red List threat statuses, it was possible to begin to develop an Africa-wide DBI (the ADBI) based on the tenets of the South African DBI for applicability across the whole continent. However, to do this, all three sub-indices of the South African DBI required some modification for use at the continental scale.

In the case of the Red List threat status sub-index of the DBI, both the national and global statuses are significant, whereas for the whole continent, there are no national Red List threat statuses, only global ones. In the case of the geographical distribution DBI sub-index, it is based on conservation-action units, i.e. the political boundaries of state provinces. This means that an alternative geographical approach had to be adopted for the African continent that was both practical and yet useful for the development of a meaningful sub-index.

The greatest challenge of all was to modify the habitat sensitivity sub-index to be effective at the continental scale. This is because the national habitat sensitivity sub-index of the DBI is based on the proportional occurrence of dragonflies in fully natural versus human-modified or artificial habitats, which is based on quantitative data. That is, the proportional occurrence of each species in a range of water body types, from fully natural to highly transformed water bodies. This led a full range of habitat sensitivity sub-index scores for the South African species. However, the challenge was that these data were not available at the continental level, and so an alternative sub-index was required for pan-African assessment. Addressing this challenge is the main focus here and is developed and described in detail below. This is a novel approach that extends far beyond the earlier work that was undertaken solely at the national level and focuses on development of the new species vulnerability sub-index. With this development, alongside modification of the geographical distribution and Red List threat status, it is possible to create a completely new index, the ADBI, the steps of which are given here.

2. Data development and methods

2.1. Databases

Only two databases were available and used here: the Odonata Database of Africa (ODA: http://addo.adu.org.za) and the African Dragonfly Habitat Matrix (ADHM). The ODA is a comprehensive spatial database of dragonfly species recorded across the African continent (e.g. Kipping et al., 2009; Dijkstra et al., 2011; Clausnitzer et al., 2012; Simaika et al., 2013), containing 125 978 individual records at the time of this analysis, and developed through convergence of international co-operation over many years. The ADHM is a matrix describing the preference of each of the 708 species identified for the African continent, across a spectrum of habitat types, i.e. the 'habitat preference' of each species. This habitat preference was categorized according to three main habitat types: 1) landscape (presence or absence of canopy cover in a forested or exposed landscape), 2) water body type (lentic and lotic), and 3) microhabitat (substrate and vegetation occurring within and surrounding the water body type).

2.1.1. The Odonata database of Africa (ODA)

The ODA is based on the verified spatial distribution records of the dragonfly species occurring across mainland Africa, which includes observations in the field, collections (both private and museum) and publications. Also included, are the records from the main islands around Africa (e.g. Madagascar, Mauritius, Seychelles, Spain Canary Islands, São Tomé and Príncipe Islands) as well as the various small islands that connect to larger mainland countries, such as Annobon Island of Equatorial Guinea. These records span the years 1700 to 2014. Along with the species' scientific names, the ODA stores the authors of the species, year of description, the species' global Red List threat status, date of observation and/or collection, and location at which it was recorded (i.e. country, province, locality, elevation, habitat description, and latitude and longitude coordinates).

Additionally, information on the life cycle stage of the specimen is included (e.g. larva, teneral, or adult), as well as its reproductive behavior where observed (e.g. tandem flight, copulation or ovipositioning). Also included, is the source of the data, i.e. the record category (e.g. observation, literature, etc.), type of data source (e.g. museum, private, etc.), collector's name, and name of the collection where the specimen is housed. Finally, comments are made as to whether there is any uncertainty with the taxonomy and/or geographical distribution. All this information is collated according to Kipping et al. (2009).

As with the IUCN/SSC Red List assessments of the various aquatic taxa located in the African mainland freshwater ecosystems (Darwall et al., 2011), this study also uses only those data from the African mainland. Also, all records with uncertainty over taxonomy and/or geographical distribution, without valid scientific names, and without valid latitude and longitude coordinates were removed. Consequently, the final ODA version that was used here, had 115 960 records (Fig. 1). These final ODA records were used to determine the geographical distribution sub-index scores of the ADBI (discussed in Section 2.2.1).

2.1.2. Development of the African dragonfly habitat matrix (ADHM)

As there were few direct observations of the African dragonfly species' sensitivity to habitat disturbances, a habitat sensitivity sub-index, as used in the South African DBI, could not be used for this pan-African study. This meant that a 'species vulnerability sub-index' had to be developed, which expressed indirectly the 'habitat preference' of each species (i.e. the occurrence of each species across a spectrum of habitat types) and the known levels of sensitivity of those habitat types to human disturbances ('habitat sensitivity'). This resulted in the ADHM being compiled, a data matrix containing the description of each African dragonfly species' habitat preference, as evaluated by a group of African dragonfly specialists during an international workshop of 15 African dragonfly experts that was held at Stellenbosch University in November 2013.

To define the habitat preference of each species, the matrix was first divided into the three main habitat types: 1) landscape (presence or absence of canopy cover in a forested or exposed landscape), 2) water body type located within the specific landscape (lentic and lotic), and 3) microhabitat (substrate and vegetation occurring within and surrounding the water body type). Each of these main habitat types was further sub-divided into several different attributes that represent the various environmental characteristics in which each dragonfly species occurs. Accordingly, 'landscape' was divided into four attributes, 'water body' into 12, and 'microhabitat' into 11 attributes (i.e. four for substrate, and seven for vegetation). This meant that, in total, 27 attributes were used to determine each African dragonfly species' habitat preference, which are based on minimum effective categorization set according to the habitat preferences of the dragonfly fauna across Africa (Table 1). The codes and full descriptions of each of these 27 attributes are listed in Appendix B (Supplementary material).

To establish the exact habitat preference of each species, values ranging from zero to three were used by the dragonfly specialists to indicate the particular preference each species has for each of these attributes. These values were: 0 – presence or absence of a species inconsequential when the attribute was considered to have no impact on the species' survival (neutral habitat preference), 1 – species' preference of attribute was inferred or suspected, but was considered not essential for survival (assumed positive habitat preference), 2 – species' preference of attribute often existed, but was not considered essential for survival (positive habitat preference), 3 – attribute is the absolute chosen habitat type, and an essential microhabitat for a species' survival (its exclusive habitat preference). This finalized habitat preference matrix was used to determine the sensitivity of these habitat types to human disturbances and accordingly, the species vulnerability to human disturbances (discussed in Section 2.2.3).

2.2. The African dragonfly Biotic index (ADBI)

The ADBI consisted of three sub-indices: 1) a species' geographical distribution, 2) its global Red List threat status, and 3) its species vulnerability to human disturbances. These three sub-indices were measured at two different spatial scales, i.e. the species' threat status was determined at a global scale, while their geographical distribution and species vulnerability to human disturbances were assessed at a continental scale. Furthermore, each of these three sub-indices was scored for each of the selected African dragonfly species. Any dragonfly species could have any one sub-index score ranging from 0 to 3, and as each individual species was assigned three sub-index scores, a species' ADBI scores had a range from 0 to 9. Below is a description on how the scores were established for each of the three sub-indices.

2.2.1. ADBI sub-index 1: Geographical distribution

As with the South African DBI, the ADBI relies on the presence/absence data of adult dragonflies (and some records of larvae and exuviae) to calculate the geographic distribution sub-index. However, unlike the South African DBI, which, for practical reasons, calculated the first sub-index according to the species' presence/absence records in the South African provinces (i.e. conservation units with their own conservation legislation) (Samways and Simaika, 2016), the geographic distribution sub-index of the ADBI is calculated at a larger, continental scale. This presented a problem, as the DBI method could not be applied at a continental level due to the fact that provinces or countries are delineated by boundaries that are governed by political decrees. Dragonflies, on the other hand, are highly mobile animals that do not recognize these human boundaries and occupy areas according to their habitat preferences. Of the species that were assessed, only 74 species are found within the particular political borders of any one African country, e.g. *Ischnura abyssinica* (Ethiopia), *Crenigomphus kavangoensis* (Namibia) and *Libellula quadrimaculata* (Morocco). Therefore, a new

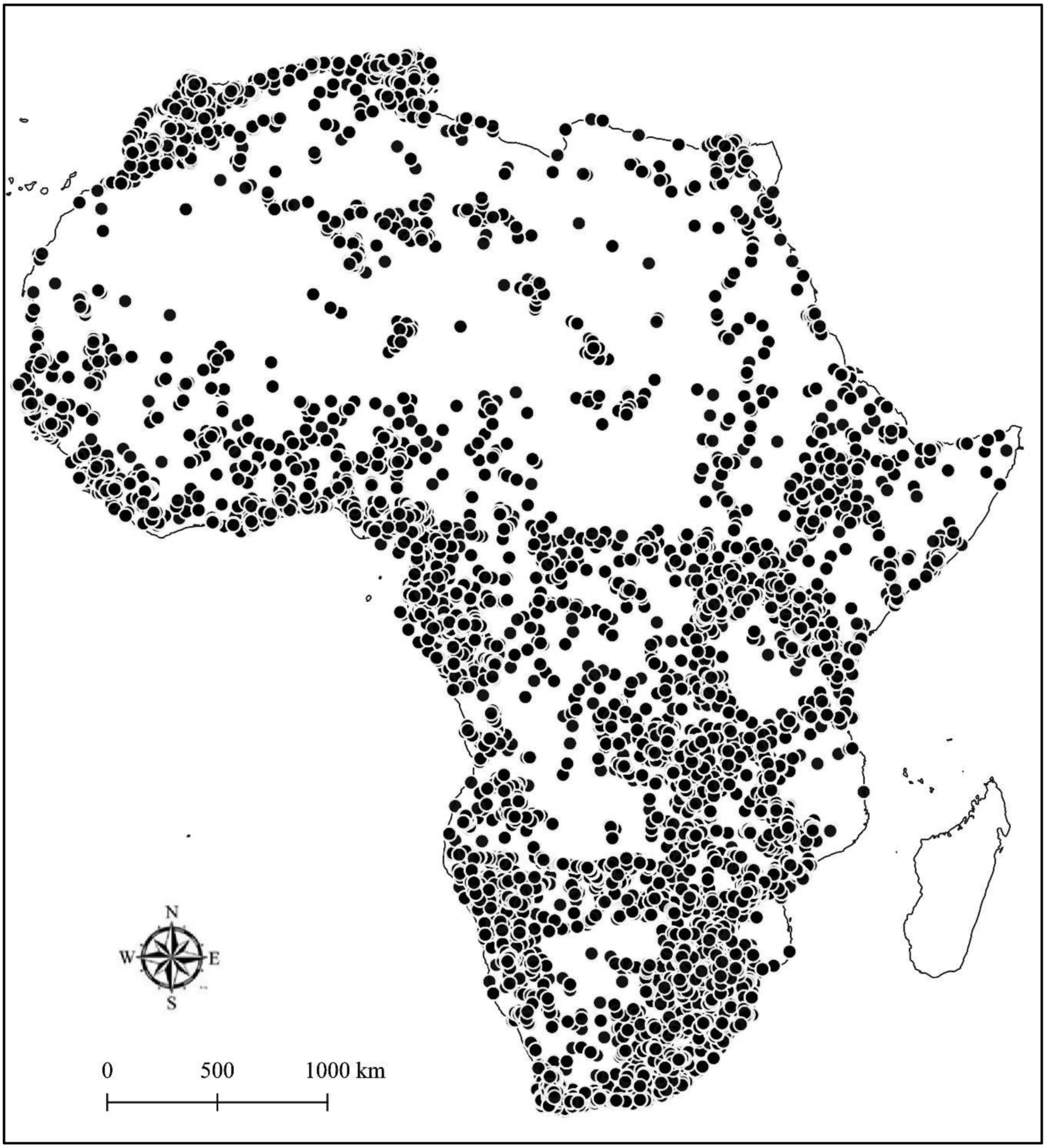

Fig. 1. Distribution of dragonfly species records used here from the Odonata Database of Africa. Each dot represents a sampling point, as of 7 November 2016. (Created using QGIS version 3.8.3-Zanzibar (QGIS Development Team, 2019)).

method for calculating the geographic distribution sub-index was needed.

As the data were measured at both large spatial and temporal scales, the distribution data being used here can be expressed from both an extensive geographical and historical perspective (Brown, 1995; Gaston and Blackburn, 2000). That is to say, numerous dragonfly species are used in this study (708 spp.), which were sampled over an extensive spatial scale (the African continent) as well as over a long time period (from 1700 to 2014). Therefore, it was possible to calculate the area between the outermost limits of each species occurrence in their respective geographical ranges, i.e. calculating each species range size (i.e. Gaston and Blackburn, 2000). Consequently, the geographical distribution sub-index scores were determined by first establishing the maximum and minimum values of the individual species' latitude and longitude (geographical) ranges, which were measured in decimal degrees (°), the details of which are in the ODA database (Section 2.1.1). Next, the differences between these maximum and minimum values were calculated. This provided the respective East/West (E/W (latitude)) and North/South (N/S (longitude)) ranges for the individual species, i.e. the latitude-longitude range sizes of each species. This method is robust and provide a good description of each assessed species' geographical range.

STATISTICA version 13 (Dell Inc., 2016) provided the most practical platform to assign each species' with geographical distribution sub-index scores. An alternative method could have been the extent of occurrence (EOO) concept, as defined by the IUCN guidelines (IUCN, 2016), which is used to define the estimated area or spatial spread in which an organism is enclosed (Cumberlidge and Daniels, 2008; Darwall et al., 2009; Suhling et al., 2009). According to the IUCN guidelines (IUCN, 2016), the main recommendation is the use of a range-estimation method, the minimum convex polygon (MCP), to express the EOO of the relevant organisms (Burgman and Fox, 2003). However, using MCP range

Table 1
An overview of the three main habitat types listed in the African Dragonfly Habitat Matrix (ADHM), i.e. landscape, water body and microhabitat. Included are the total number of attributes of each habitat type, as well as a short list of these attributes for each of the three main habitat types. A fuller explanation for each attribute is listed in Appendix B (supplementary material).

Landscape	Water body	Microhabitat
● Assessed according to the presence or absence of canopy cover (in forested or open landscape). ● A total of 4 attributes: - shaded habitat in forested landscape - exposed habitat in forested landscape - shaded habitat in open landscape - exposed habitat in open landscape	● Assessed according to water body type within the specific landscape, i.e. lentic or lotic. ● A total of 12 attributes: - seeps - headwaters - streams - channels - rivers - lakes - stagnant water - phytotelmata (e.g. tree holes) - ephemeral/temporary waters - oligotrophic conditions (e.g. blackwater) - slow water movement - rapid water movement	● Assessed according to the substrate and vegetation occurring within and surrounding the water body type, located within the specific landscape. ● A total of 11 attributes: ● Substrate (4 attributes) - large rocks, boulders - gravel - sand - soft substrate (e.g. mud) ● Vegetation (7 attributes) - woody debris - coarse detritus - submerged roots/twigs - overhanging branches - aquatic plants - emergent plants (e.g. reeds) - bare soil

estimations (i.e. EOO of a species) can be problematic as they are too coarse a scale, and can over-estimate the potential range in which the species may occur (Jetz et al., 2008), and it needs at least three documented presence records to determine the spread of a species. Consequently, using minimum convex polygons to estimate the spatial spread of aquatic organisms is not recommended, as it can be extremely misrepresentative of species spread (Simaika and Samways, 2010).

The latitude and longitude ranges were plotted against each other as coded scatterplots (i.e. coded according to each individual species), with each species allocated to a chart. For both the E/W (latitude) and N/S (longitude) ranges, the axes were scaled from 0° to 100° in step sizes of 5° (Fig. 2). The scoring system of this sub-index was: A) species occurring within the latitude-longitude range size of 0° to 5.00° have a very narrow distribution range and received a score of 3, B) species within the latitude-longitude range size of 5.01° to 25.00° have a narrow distribution range and received a score of 2, C) species within the latitude-longitude range size of 25.01° to 50.00° have a wider distribution range and received a score of 1, and D) species occurring above the latitude-longitude range size of 50.01° have a very wide distribution range and received a score of 0 (Fig. 2, Table 2).

A cautionary note is that at the very large continental scale, care must be taken to compare like with like. Such a comparison over time (i.e. deterioration or recovery of a site over time) is straightforward, as the same spatial extent is being compared. Also, at the small spatial scale, sites can be compared, for example, to determine complementarity, or whether one site had deteriorated in comparison with another. Yet, when comparing two widely differing areas, care in the interpretation is required. For example, the Greater Cape Floristic Region has many high-scoring species, while the Okavango Delta has many low-scoring species, resulting in very different average scores per taxon. However, this does not mean that the Okavango is of lesser conservation value than the Cape, only that the Cape has more irreplaceable species than the Okavango, and the risk of extinction is higher. This where it is also important to stipulate species richness and

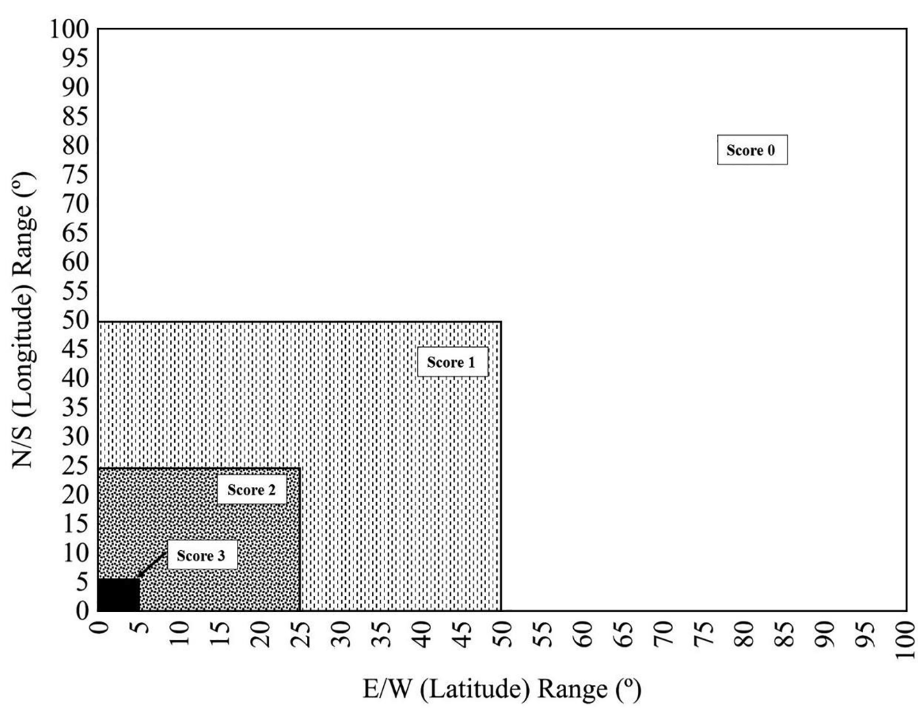

Fig. 2. An illustrative sketch of how each dragonfly species' geographical distribution sub-index score was calculated, by plotting the E/W (latitude) range (x-axis) against the N/S (longitude) range (y-axis). The scores were established depending on where the markers for each species were drawn. Thus: a marker between the latitude-longitude range size of 0° and 5.00° was assigned a score of 3; a marker between the latitude-longitude range size of 5.01° and 25.00°, a score of 2; a marker between the latitude-longitude range size of 25.01° and 50.00°, a score of 1; and a marker over the latitude-longitude range size of 50°, a score of 0.

Table 2
Description of the three sub-indices of the African Dragonfly Biotic Index (ADBI), i.e. 1) Geographical distribution, 2) Threat status, and 3) Species vulnerability to human disturbances. The scores of these three sub-indices range from 0 to 3, with the total ADBI score being the sum of the scores of the three sub-indices ranging from 0 to 9. Thus, a common, widespread, non-threatened and highly tolerant (of human disturbances) species receives a score of 0 (0 + 0 + 0), whereas a highly restricted, endangered, and extremely sensitive species scores a 9 (3 + 3 + 3). Abbreviations for the IUCN/SSC Red List threat status (IUCN, 2016): LC – Least Concern, NT – Near Threatened, DD – Data Deficient (i.e. the value is a precautionary measure), VU – Vulnerable, EN – Endangered, and CR – Critically Endangered. Other abbreviation: lat-long – latitude-longitude.

Scores	Sub-indices		
	Geographical distribution	Threat status	Species vulnerability
0	A very wide distribution range size (species have a lat-long range size of more than 50° of continental Africa)	LC	Low vulnerability to certain human disturbances (all 3 habitat types* may be disturbed)
1	A wide distribution range size (species have a lat-long range size between 25° and 50° of continental Africa)	NT, DD	Shows some vulnerability to certain human disturbances (2 habitat types* may be disturbed)
2	A narrow distribution range size (species have a lat-long range size between 5° and 25° of continental Africa)	VU	Is vulnerable to certain human disturbances (1 habitat type* may be disturbed)
3	A very narrow distribution range size (species have a lat-long range size of less than 5° of continental Africa)	EN, CR	Extremely vulnerable to certain human disturbances (no habitat type* is disturbed)

*The habitat types include the occurrence of landscape, water bodies, and microhabitats.

composition in addition to the ADBI score/site, with the Okavango for example being far more species rich per area (e.g. 10 km^2) than the Cape. Furthermore, gamma diversity must also be considered, with the two areas sharing few species.

2.2.2. ADBI sub-index 2: Threat status

The threat status sub-index score was determined by using the global IUCN/SSC Red List threat statuses, as established by the IUCN Red List Categories and Criteria, version 3.1 (second edition). This is the only globally recognized standard methodology for assessing the threat status of species according to standardized methods across the world. It is also the only approach that has been used to assess the threat status of African dragonfly species (IUCN, 2016). The threat statuses that were applied are: Least Concern (LC), Near Threatened (NT), Data Deficient (DD), Vulnerable (VU), Endangered (EN) and Critically Endangered (CR). The scoring for this sub-index is given in Table 2. In addition, the classification 'Data Deficient' received a sub-index score of 1 as a precautionary measure, because not enough information is available on the species classified as 'DD'.

2.2.3. ADBI sub-index 3: Species vulnerability

For the species vulnerability sub-index, it was necessary to consider where each species lives and reproduces (i.e. its habitat), and the risks that its habitat faces relative to types of transformation of its habitat, and the magnitude of the various threats. From this reasoning, three facets were used when the species' vulnerability sub-index score was calculated: 1) a species' habitat preference as described in the ADHM (Section 2.1.2), 2) the habitat's degree of sensitivity to human disturbances (habitat sensitivity), and 3) the stressor, i.e. the impact of human disturbances. To determine the sensitivity of each species' habitat preference to human disturbances, the impact of the human disturbances or stressors had to be considered. Consequently, three key stressors that may have an impact on dragonfly assemblages and which have the potential to be quantified, were identified: 1) habitat conversion (mostly deforestation, agricultural conversion, mining, and/or urbanization), 2) water management, such as construction of dams and reservoirs, and 3) presence of alien trees, which can shade out certain sunlit dragonfly habitats.

The first step was to use expert knowledge to give a weight to each attribute of the three main habitat types ('habitat preference'), while taking into account the possible impacts of the stressors. The expert knowledge was provided by the 15 African dragonfly specialists, who collectively had over 200 years of combined field experience with African dragonflies. All disputes were resolved by discussion, with most differences of opinion arising from different researchers having worked in particular geographical areas. This resolution enabled the finest possible assessment of the habitat preferences of, and stressors to, each of the species in turn.

The attributes of the habitat type groups 'landscape' and 'water body' received a weight of 1 to 4, while the attributes of the habitat type 'microhabitat' received a weight of 1–3 (Supplementary material Appendix B), based on reasoned, natural differences. The increase in weights indicated an increase in impact the stressors may have on the presence of dragonflies for each specific attribute. Thus, a weight of 1 indicates that the stressors will have minimal or no impact on the presence of a particular dragonfly species, while a weight of 4 (or 3 in the case of the habitat type 'microhabitat') indicates that the stressors have a severe impact on the presence on a dragonfly species.

The second step was to multiply the above weights that were given to each of the 27 attributes with the relevant value of the specific attributes (indication of preference). This offered a weighted attribute-sensitivity value for each attribute of each habitat type, i.e. a total of 27 weighted attribute-sensitivity values for each species. For example: if the attribute 'forested landscape' (code 'Fx' in Supplementary material Appendix B) of a species was given a specialists' value of 3 (the absolutely preferred landscape), while the weight of this attribute is 4 (e.g. complete deforestation can extirpate the species' population), the weighted sensitivity of this attribute for the species will be 12. Consequently, deforestation will have a severe impact on a specific dragonfly species' presence in a forested landscape. These calculations were done for each of the 27 attributes for each of the 708 species.

For the third step, the weighted attribute-sensitivity values of the particular main habitat types were added together to provide the 'Total Weighted Attribute Sensitivity' (TWAS) for each species, i.e. each species had three respective TWAS values, one for each habitat type. Also, the valued attributes (indication of preference) of the respective main habitat types, as given by the dragonfly specialists, were added together to provide the 'Total Habitat Preference' (THP) for each species, i.e. each species had three respective THP values. To determine how sensitive each habitat type may be to the impacts of the stressors, the TWAS was divided by the THP of the respective habitat types for each species. As a result, each of the 708 species now had one habitat sensitivity value for each of the three main habitat types, which ranged from 1 to 4 for the habitat types 'landscape' and 'water body', and in the case of the habitat type 'microhabitat', from 0 to 3.

However, these values were fractions, and had to be converted to single values. Therefore, the fourth step was to convert the fragmented habitat sensitivity values for each of the three habitat types into a single habitat sensitivity value for each habitat type for each dragonfly species. This was done by using the IF function in Microsoft Excel, i.e. a function that checks whether a certain value or condition is met and returns a specific value if this condition is true. As there are three

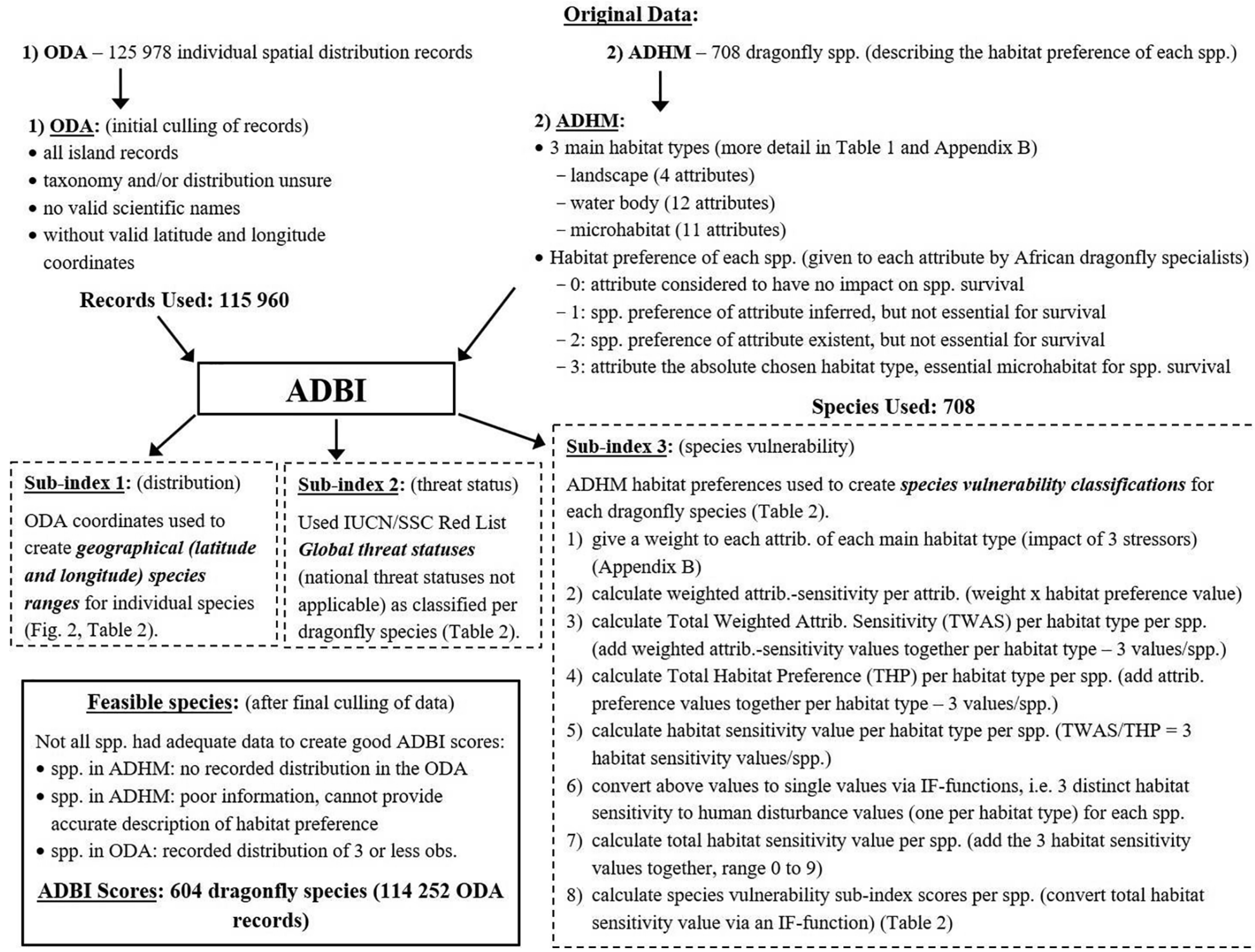

Fig. 3. A schematic representation of the process in creating the African Dragonfly Biotic Index (ADBI) scores for the 604 dragonfly species (using 114 252 ODA records). This figure shows how the data were used throughout the process.

habitat types and one of them has a different value range regarding its habitat sensitivity, two distinct IF functions with their relevant ranges were created. These functions were:

$$\textit{Landscape and water body sensitivity} = IF(value \leqslant 1.9,\ 0,\ IF(value \leqslant 2.9,\ 1,\ IF(value \leqslant 3.9,\ 2,\ IF(value \geqslant 4.0,\ 3))))$$

$$\textit{Microhabitat sensitivity} = IF(value \leqslant 0.9,\ 0,\ IF(value \leqslant 1.9,\ 1,\ IF(value \leqslant 2.9,\ 2,\ IF(value \geqslant 3.0,\ 3))))$$

Consequently, each dragonfly species now had three types of distinct habitat sensitivity to human disturbance values, i.e. landscape sensitivity, water body sensitivity, and microhabitat sensitivity. These three sensitivity values were added together to provide a total habitat sensitivity value, ranging from 0 to 9, for each of the 708 dragonfly species. However, like the other two sub-indices of the ADBI, the species vulnerability sub-index scores requires practicality and therefore range from 0 to 3, while bearing in mind that this sub-index is more subjective than the other two. To determine this value range, each of these total habitat sensitivity values was converted to a species vulnerability sub-index score by using another IF function. This IF function was:

$$\textit{Species vulnerability sub} - \textit{index} = IF(value = 0,\ 0,\ IF(value = 1,\ 0,\ IF(value = 2,\ 0,\ IF(value = 3,\ 1,\ IF(value = 4,\ 1,\ IF(value = 5,\ 2,\ IF(value = 6,\ 2,\ IF(value \geqslant 7,\ 3))))))))$$

The following numerical ranges were used to determine the sub-index scores 0 to 3: species with a total habitat sensitivity value of 0–2 received a score of 0, species with a total habitat sensitivity value of 3–4 received a score of 1, species with a total habitat sensitivity value of 5–6 received a score of 2, and species with a total habitat sensitivity value of ≥7 received a score of 3. Hence, the species vulnerability sub-index scores were: 1) species with a score of 0 are not particularly vulnerable to any human disturbances (all habitat types may be disturbed), 2) species with a score of 1 show some vulnerability to human disturbances (two habitat types may be disturbed), 3) species with a score of 2 are vulnerable to human disturbances (one habitat type may be disturbed), and 4) species with a score of 3 are extremely vulnerable to human disturbances (no habitat type is disturbed) (Table 2).

2.3. Separating feasible species from species that are pending

A total of 708 recorded dragonfly species are recognized for the African continent (as listed in the ADHM). However, after completing all the calculations for the three sub-indices, it was found that not all of these species had adequate data for the three sub-indices to create satisfactory ADBI scores. And so, the species without the necessary data are listed as 'pending, requiring further data'. To determine which of these species should be classified as 'pending', there are three categories that separated them from the 'feasible species' (i.e. those that had adequate data to create ADBI scores).

These categories are: 1) species within the ADHM that, to date, have no recorded geographical distribution listed in the ODA (e.g. *Trithemis morrisoni*), 2) species which have a recorded distribution of three or less observations in the ODA (e.g. *Idomacromia jillianae*), and 3) species within the ADHM that have inadequate information to provide a relatively accurate description of their habitat preference, i.e. there is not enough information available to successfully evaluate the habitat attributes (e.g. *Micromacromia flava*). The result of this culling meant that of the 708 species, 104 had to be classified as pending. Therefore, only 604 feasible species (114 252 ODA records) received an ADBI score. To include the other species at this stage, in our odonatological knowledge, would lead to erroneous results. These species with their three sub-index scores and final ADBI scores are listed in Appendix C (Supplementary material). An overview of creating the ADBI is given in Fig. 3, i.e. from the original databases to the final identification of the feasible species.

2.4. Data analysis

All data analyses and graphs (using STATISTICA version 13 (Dell Inc., 2016)) were completed using the 604 species for which the three sub-indices and ADBI scores could be calculated. Using the relevant data, the frequency of dragonfly species was calculated for the sub-index scores and final ADBI scores.

3. Results

3.1. The three sub-indices of the ADBI

Of the 604 dragonfly species that could be assessed, many (47%) were classified as having a narrow distribution range (i.e. have a latitude-longitude range size between 5° and 25° of continental Africa) and were assigned a sub-index score 2 (Fig. 4a). These 285 species occurred within a 20° band width, either north or south of the equator. Furthermore, the second group of dragonfly species (1 4 8) were classified as having a wide distribution range size (latitude-longitude range size between 25° and 50° of continental Africa) and were assigned the sub-index score 1, while the third group of 93 dragonflies were classified as having a very wide distribution range size (latitude-longitude range size of more than 50° of continental Africa) and were assigned the sub-index score 0 (Fig. 4a). Only 78 species (the fourth group) occurred within a very narrow distribution band of 5° or less and were assigned the sub-index score 3 (Fig. 4a).

As there was sufficient information available on the global threat status of the assessed dragonfly species, ≥80% were classified as of 'Least Concern', i.e. 531 species were given the sub-index score 0 (Fig. 3b). Whereas, only a few species were classified according to the other threat status categories, i.e. 35 species were classified as 'Near Threatened' or 'Data Deficient' (sub-index score 1), 19 species as 'Vulnerable' (sub-index score 2), and 19 species were classified as 'Endangered' or 'Critically Endangered' (sub-index score 3) (Fig. 4b).

Regarding the third sub-index, species vulnerability to human disturbances, more than two thirds of the 604 dragonfly species either showed some vulnerability to human disturbances (i.e. 261 species; two habitat types may be disturbed; assigned sub-index score 1) or are vulnerable to human disturbances (i.e. 226 species; one habitat type may be disturbed; assigned sub-index score 2) (Table 2, Fig. 4c). For the first group of species (sub-index score1), some of them may occur in artificial water bodies, such as reservoirs, e.g. *Anax imperator*, *Brachythemis leucosticta* and *Crocothemis erythraea*. The second group of species (sub-index score 2) occur mainly in natural, undisturbed water bodies than in artificial habitats, e.g. *Syncordulia gracilis*, *Gynacantha usambarica* and *Proischnura polychromatica*. On the other hand, only 66 species were classified as having a low vulnerability to any human disturbances, i.e. were assigned sub-index score 0 (Table 2, Fig. 4c). The species within this group can occur in greatly disturbed or human habitats, e.g. individuals of *Acisoma trifidum* have been found in mining pits in heavily disturbed forests. Finally, 51 of the assessed species were restricted to natural areas only and were assigned the sub-index score 3 (Table 2, Fig. 4c). An example is *Spesbona angusta*, which has been only recorded in a small area, is highly threatened, and is extremely habitat-specific within a small area in the Greater Cape Floristic Region, South Africa (Deacon and Samways, 2017).

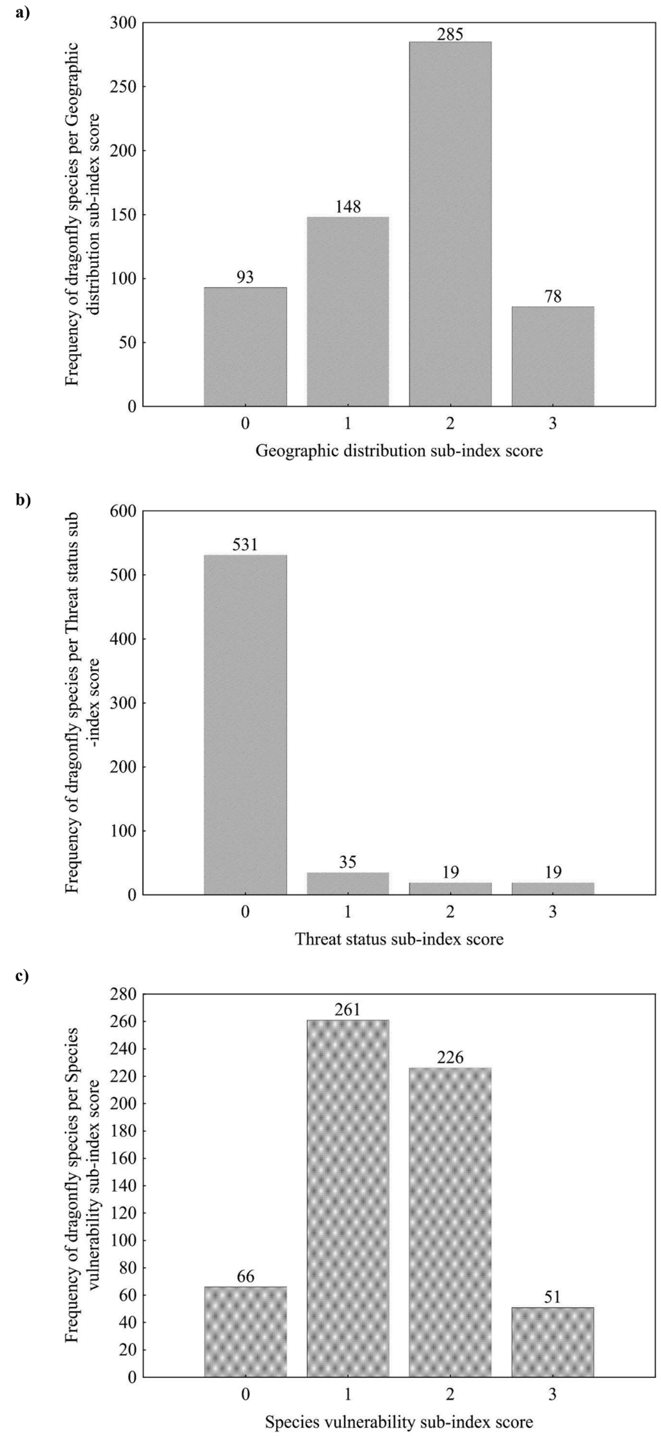

Fig. 4. The frequency of dragonfly species (total = 604) that were allocated to the sub-index scores (0 to 3) of the three ADBI sub-indices, i.e. a) Geographical distribution, b) Threat status, and c) Species vulnerability.

3.2. The ADBI scores

The ADBI scores ranged from 0 to 9. At the lower end (i.e. 0–4), the species are the widespread habitat generalists that are least vulnerable to human disturbances (Fig. 5), and the species with a score of 0 being

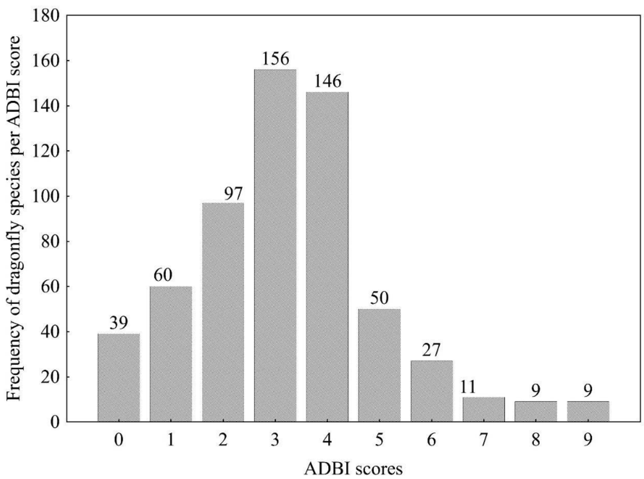

Fig. 5. Frequency of dragonfly species (total = 604) that were allocated the respective African Dragonfly Biotic Index (ADBI) scores (i.e. 0–9).

those that regularly occur in disturbed or artificial conditions. For example: *Trithemis arteriosa* (ADBI score 0; Supplementary material Appendix C) is geographically widespread, occurs regularly in freshwater ponds, lakes, reservoirs, slow reaches of rivers and even irrigation channels. On a global scale, this species has no known major threats, but it could decline locally from pollution and over-abstraction of water in desert areas (Boudot et al., 2013).

The more habitat specialist species have ADBI scores ranging from 5 to 9, with these species being increasingly vulnerable to human disturbances the higher their ADBI scores (Fig. 5). Species with an ADBI score of 9 cannot tolerate any human disturbance, and only occur under fully natural environmental conditions. For example: *Amanipodagrion gilliesi* (ADBI score 9; Supplementary material Appendix C) only occurs in small, canopied forest streams, has a very restricted distribution range, and occupies only a very small area ($\leq 10\ km^2$) in the Sigi Forest, East Usambara Mountains in Tanzania (Clausnitzer, 2003). It is estimated that this species' population consists of < 500 individuals, and which is declining due to increased human population pressure causing forest destruction and pollution (Clausnitzer, 2010).

Both the lowest ADBI scores (0–1) and highest ADBI scores (8–9) have a relatively low number of species per score: ADBI score 0, 39 species; ADBI score 1, 60 species; and both ADBI scores 8 and 9 having only 9 species per score (Fig. 5). The peak number of species per score occurs at the average ADBI scores of 3 and 4 (Fig. 5). This spread in species across the ADBI scores is similar to the spread of South African species across the South African DBI scores (Samways and Simaika, 2016). Therefore, a quarter of the assessed species were given an intermediate ADBI score of either 3 (represented by 156 species) or 4 (represented by 145 species) (Fig. 5).

The species with an ADBI score of 3 have a wide to narrow distribution range (sub-index scores 1 and 2 respectively), are not threatened (sub-index score 0), and show some vulnerability to human disturbances (sub-index scores 1 and 2 respectively; Table 2). Examples are: *Macrodiplax cora*, *Palpopleura albifrons* and *Pseudagrion estesi* (Supplementary material Appendix C). On the other hand, species with an ADBI score of 4 vary more in their classifications. That is, these species have a distribution range that varies from wide to very narrow (sub-index scores 1–3), are non-threatened or near threatened (sub-index scores 0 and 1 respectively), and their vulnerability to human disturbances varies from showing some vulnerability to being extremely vulnerable to any changes in their habitats (sub-index scores 1 to 3; Table 2). Examples are: *Micromacromia zygoptera*, *Pinheyschna waterstoni* and *Chlorolestes conspicuus* (Supplementary material Appendix C).

4. Discussion

The African Dragonfly Biotic Index (ADBI) is a first framework and baseline for understanding comparative threats to freshwater systems, both lotic and lentic, at a continental level. It also has the potential to be refined as a starting point for development of other national DBIs beyond that of South Africa. It is also a monitoring tool for African freshwater systems over the coming years, and a vehicle for identifying where, when, and the extent to which conservation should be actioned. An important point is that the subjects, dragonflies are readily appreciated by rural communities and have already been developed as education and communication tools (Clausnitzer et al., 2017). They can also be used for other purposes, such as comparison of urban and rural environments, whether associated with lotic (Kietzka et al., 2018) or lentic systems (Goertzen and Suhling, 2019), and to assess complementarity among ponds (Briggs et al., 2019). But, the use of dragonflies, although effective in their own right, does not exclude other taxa also being used in freshwater quality assessments. Such complementary taxon sets include mayflies, stoneflies and caddisflies (Kietzka et al., 2019), other macroinvertebrates and filamentous algae (Petersen et al., 2018), or water beetles and caddisflies (Buczyńska and Buczyński, 2019).

4.1. Influences of species vulnerability sub-index scores on final ADBI scores

Calculating the scores of the ADBI's first two sub-indices, geographical distribution and threat status, were straightforward. In contrast, the calculations for the species vulnerability sub-index was elaborate and subjective, being based on the expert opinion of dragonfly ecologists. The weights given to each attribute of the three main habitat types (to express the possible influence of the selected stressors on the dragonfly species' habitats) were dependent on how each of the three main stressors might negatively affect the presence of the species according to a particular attribute.

The type of stressors also had an effect on how the weights were given. For example, deforestation would be most severe for forested areas (e.g. Renner et al., 2018), or for transformation to plantations (e.g. Dalzochio et al., 2018), while the growth of alien riparian trees is a critical threat to open, sclerophyllous landscapes (e.g. Samways, 2006; Samways and Sharratt, 2010; French and McCauley, 2018). Likewise, the scale of the weights also differed for the three main habitat types. As in the case of the category 'landscape', only one weight of '4' could be assigned to an attribute (i.e. had only four attributes), whereas the category 'water body' could be assigned more than one weight of '4' for its attributes (i.e. comprised of 12 attributes). The reasoning here for this was that the number of weights (i.e. the number of 'fours', 'threes', etc.) that were assigned to the respective attributes had an effect on the initial calculations from habitat preference to habitat sensitivity. Therefore, these sub-index scores may be more restrained than for the other two sub-indices and so, this third sub-index would have affected the final ADBI scores for each of the assessed dragonfly species.

The main focus on calculating this sub-index was on habitat preferences of the dragonfly species (i.e. their immediate physical environment) and how, through human modification of habitats, their presence within these habitats can be negatively affected. As discussed by Parmesan (2006), Butchart et al. (2010), and Pereira et al. (2010), the world is constantly being altered, causing adverse changes to natural ecosystems and biodiversity loss. This is causing the natural communities and assemblages to become more homogenized, i.e. specialist species will be gradually replaced by those that are more widespread and with wider habitat preferences (McKinney and Lockwood, 1999; Olden et al., 2004; Olden, 2006, Kietzka et al., 2018; Goertzen and Suhling, 2019). This means that assessing only the physical habitats of the dragonfly species may cause some problems in future calculations of the ADBI, particularly when national indices are calculated.

A possible solution is to also include the characteristics or functional traits of the dragonfly species (both larval and adult) when calculating future ADBI scores, especially when national ADBI's are being determined. For example, changes in landscape can influence the success of dragonfly species regarding their reproduction, which can affect the composition and richness of the species at a given site. Assessing the oviposition behavioral traits (e.g. epiphytic oviposition behavior) of dragonfly species at their preferred habitats can provide an indication of how human disturbances can impact their habitats and thus their oviposition success (Rodrigues et al., 2019). This can give an indication of how sensitive a particular site is to habitat transformation due to human disturbances. Also, examining different functional traits, such as habitat specialization and migratory behavior, could indicate differences in species richness and their assemblage composition over time. For example, Eskildsen et al. (2015) determined that the group structures and species richness of Danish butterflies are related to multiple functional traits of the butterflies, and that it is necessary to take the different aspects of ecological specialization into consideration when assessing possible extinction risks within an area.

Another possible feature that can also be considered when calculating the third sub-index of the ADBI, is the adaptive capacity (both fundamental and intrinsic) of a species, such as its ability to cope with effects of climate change via three essential components: a species' genetic diversity, behavioral adjustments, and dispersal ability (Beever et al., 2016). Incorporating potential functional traits and adaptive capacity of the dragonfly species within the calculations of the ADBI could possibly remove the subjectivity of using a weighted system to calculate species vulnerability to human modifications. However, this would require much more detailed information on dragonfly species' characteristics, data for which is still lacking (e.g. those species that are classified as still pending due to, for example, having inadequate information to provide an accurate description of their habitat preference). Nevertheless, this combination of habitat preferences, functional traits, and adaptive capacity could improve future calculations of the ADBI, and this could also be applied at the ecosystem level, and so improve conservation of these ecosystems.

4.2. Applying the ADBI

Use of dragonflies for monitoring both lotic and lentic freshwater ecosystems is of value in many countries, i.e. from South Africa (Samways and Simaika, 2016) to Brazil (Dutra and De Marco, 2015; Valente-Neto et al., 2016), to Europe (Austria: Chovanec et al., 2015; Italy: Golfieri et al., 2016; and France/Switzerland: Rosset et al., 2013). Each of these regions has selected an approach that suits local conditions and approaches to conservation. The ADBI has widespread appeal, as it covers aspects (i.e. the three sub-indices) that have wide applicability. But as shown here, this index depends on having data on the response of each species to a range of habitat conditions, ranging from fully natural through to highly disturbed or changed habitats. This is currently not possible for all of Africa, owing to lack of data at this large continental scale, and so the development of a species vulnerability sub-index (as opposed to the habitat sensitivity sub-index of the South African DBI) was necessary when addressing this large spatial scale on a still poorly-studied continent.

Each species' ADBI value is not fixed, especially as there could be a change in the IUCN Red List threat status, or more importantly, changes in the species vulnerability due to changes in the species' habitats. This means that new regional, national, or local DBIs (according to the need and feasibility of conservation action) can be developed for these areas based on the principles of the DBI developed in South Africa. Indeed, with more data, there could be a translation of the species vulnerability sub-index scores into new regional, national or local habitat sub-index scores, which are more objective (i.e. based on actual occurrences in variously disturbed water body types). This could be done in some countries where there are already good data, as in the case of some East African countries.

5. Conclusion

The ADBI is a useful assessment framework for determining the quality of lotic and lentic freshwater ecosystems on the African continent. However, it is not fixed, as ADBI scores for each dragonfly species can possibly change as more information is gathered, as when more distribution records become available or when there is a change in IUCN Red List threat status. Also, the ADBI does not preclude the use and/or creation of other freshwater monitoring tools, which may be complementary, as SASS is to the South African DBI. The ADBI was specifically created for the rapid assessment of the integrity of freshwater ecosystems. This is a baseline, and to reflect accurate measurement ecosystem health, which can later be converted into regional, national, or local DBIs as appropriate for the conservation task at hand.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ecolind.2019.105819.

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