



Realising the potential of herbarium records for conservation biology



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ABSTRACT

One of the major challenges in ecosystem conservation is obtaining baseline data, particularly for regions that have been poorly inventoried, such as regions of the African continent. Here we use a database of African herbarium records and examples from the literature to show that, although herbarium records have traditionally been collected to build botanical reference “libraries” for taxonomic and inventory purposes, they provide valuable and useful information regarding species, their distribution in time and space, their traits, phenological characteristics, associated species and their physical environment. These data have the potential to provide invaluable information to feed into evidence-based conservation decisions.

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1. Introduction

Globally, biodiversity is increasingly under threat due to changes in land use, climate and socio-economic factors. There is thus an increasing need for the long-term monitoring of biodiversity to ensure its effective conservation (Magurran et al., 2010). Few such monitoring projects have been in place for extended periods of time, particularly across the tropics and in the southern hemisphere (Magurran et al., 2010). Many countries have suffered from long financial and political instability

and may lack up-to-date knowledge of their biodiversity (e.g. Figueiredo et al., 2009). Particularly in these areas it may be difficult to obtain baseline knowledge of species, communities and ecosystems with which to monitor how climate, land use and livelihood changes are affecting biodiversity, and thus to make informed conservation decisions (Lister, 2011). While the possibility exists to obtain data from old field-based studies, re-visit the sites of these studies, and repeat the sampling procedures to compare current and historical biodiversity (e.g. Thiollay, 2006), such inventory data are often scarce and difficult to obtain, and “thinking-outside-the-box” methods are called for (Sparks, 2007). More specifically, biological collections, though often not systematically collected (see Appendix A), have the potential to provide a variety of information not only about individual species, but also about their communities and habitats (Sparks, 2007).

One of the main, and original, purposes of herbarium collections is to serve as taxonomic ‘repositories’: storing specimens allows users to return to them over decades and centuries to check the identification of plants and study the characteristics of the given species. Reference collections used to identify species, to describe new species, or to produce

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classifications of related species based on their morphological (e.g. Ross, 1973) – and, more recently, also genetic (e.g. Beck and Semple, 2015) – characteristics are of crucial importance for taxonomic purposes. Existing herbarium collections also house species awaiting description (Bebber et al., 2010). The taxonomic role of herbaria remains essential for measuring and setting conservation challenges and priorities (e.g. Rivers et al., 2010), as most conservation targets are based on taxon diversity (e.g. Küper et al., 2006) and, to a lesser extent, taxonomic relatedness (Winter et al., 2013); without the knowledge of what entails a species, such target-setting becomes impossible.

Over time, plant collections have been deposited in herbaria for various other functions besides understanding taxonomic relationships: to illustrate variation in morphology, to prepare floras and monographs, to provide voucher specimens for medicinal research and, by assembling data on phenology, to maximise the collection of fertile material of special significance to seed collections. Nevertheless, new purposes for herbarium specimens frequently arise, so that they are utilized for purposes for which they were initially not intended (Pyke and Ehrlich, 2010).

Here, we illustrate, using a case study, the contributions that herbarium specimens can make to providing a range of baseline data in space, thereby adding to the understanding and monitoring of biodiversity which can directly be used for conservation purposes. This work summarizes and builds on several previous studies that have emphasized the uses of herbarium data (e.g. Elith and Leathwick, 2007; Kalema, 2008; Loiselle et al., 2008; Cherry, 2009; Aikio et al., 2010; Pyke and Ehrlich, 2010; Vorontsova et al., 2010; Greve and Svenning, 2011). We employ an extensive dataset of African *Acacia* (sensu lato, including *Senegalia*, *Vachellia* and *Faidherbia*) for this purpose (Greve et al., 2012). In addition, we highlight the role that herbarium collections can make to monitoring biodiversity in time in the discussion.

2. Materials and methods

A large database of herbarium records of African *Acacia* was set up (Greve et al., 2012) using the BRAHMS databasing system (Filer, 2011). The database contains the majority of the collections housed in the following herbaria: National Botanical Garden of Belgium (BR), University of Coimbra (COI), East African Herbarium (EA), Royal Botanic Gardens Kew (K), Instituto de Investigação Científica Tropical (LISC), Missouri Botanical Garden (MO), and PRECIS data, which contains the digitized information of South African herbaria, mostly those of the National Herbarium of South Africa (PRE), Compton Herbarium (NGB) and KwaZulu-Natal Herbarium (NH), as well as extensive collections from several other African and European herbaria. In all, the database consists of approximately 31,000 unique entries, of which approximately 23,000 are georeferenced. The database not only contains the specimen identity data, but, for most specimens, the label information of the collections. This label information includes fields such as dates of collections, identity of collectors, geographical descriptors, characteristics of the plant, habitat information and common or local names, depending on what the collector recorded, and, for specimens not digitized by us, on what was copied from the labels into the database.

The collection locality of most herbarium specimens is indicated on the herbarium labels. Where GPS coordinates are not provided with the collection locality, the description locality can often be used to georeference the collection location using gazetteers and other mapping tools. This was done for the *Acacia* database: specimens that had no GPS coordinates associated with them were georeferenced if their locations could be determined with some accuracy (locations had to be more accurate than to district level).

To show the mapping application of herbarium specimens, the distribution of *Acacia sieberiana* DC was mapped in several different ways. All georeferenced *A. sieberiana* specimens were extracted from the *Acacia* database. Initially, the collection localities of *A. sieberiana* were mapped. As such raw collection localities only provide information on the specific areas where individual specimens have been collected,

they provide limited information on where species could potentially occur. Thus, a second map of *A. sieberiana* was produced using boosted regression tree modelling (BRTs), a species distribution modelling technique, to better present the distribution of *A. sieberiana* across Africa. Models were constructed following the methods presented in Elith et al. (2008). All georeferenced localities of *A. sieberiana* were extracted from the *Acacia* database. Nine descriptors of environmental conditions were used to model the distribution of the species: altitude (Earth Resources Observation and Science, 1996), annual mean temperature, maximum temperature of the warmest month, mean temperature of the warmest quarter, annual precipitation, precipitation seasonality, precipitation of the driest quarter, precipitation of the coldest quarter (Hijmans et al., 2005) and fire incidence, a measure of the number of years an area burnt between 2000 and 2007, derived from Tansey et al. (2008). More details on model settings are provided in Appendix A.

Knowledge of the relationship between organisms and their environment allows predictions to be made of how distributions might shift under a climate change scenario. Therefore, we used the BRT model to project the distribution of *A. sieberiana* into the future (2080) using the UKMO-HadCM3 model under an A1B scenario (IPCC, 2007). For the future projections, the current climate variables on which the model had been trained were replaced with the equivalent climate variables for the future. To understand which areas will become more and less favourable for *A. sieberiana* in the future, the current probabilities of occurrence of the species were subtracted from the future probabilities.

To map a plant characteristic, the labels of all *A. sieberiana* specimens were searched for information on tree height. All specimens that had information on estimated tree height were extracted and mapped, with the locality records labelled to represent tree height.

Herbarium specimens can also provide information about plant phenology. Some of the herbarium specimens of *A. sieberiana* were examined to record presence of flowers, and for specimens that could not be accessed in herbaria, label information was examined for an indication that the trees from which these specimens had been collected were in flower at time of collection. Because each herbarium specimen was associated with a collection date, the spatial distribution of flowering phenology (i.e. month of flowering) for the species that were in flower at the time of collection could be mapped in space.

Best practices in specimen label writing include recording information about the specimen's environment. Therefore, herbarium collections can also provide information about the environment. As an example, we mapped a soil type, namely vertisols, across Africa. This was done by searching the *Acacia* database for the word 'vertisol' or one of the synonyms of vertisols ('cracking clays', 'black cotton soils', 'basalt clay' and 'black clay': Spaargaren, 2008). In addition, the distribution of an African vegetation type – *Combretum* woodlands – was plotted. Again, a search for the word '*Combretum*' was made in the label information column of the *Acacia* database, and all records of *Acacia* specimens that were described as growing in a locality where one or several *Combretum* species were dominant were extracted from the *Acacia* database. Using the geographic coordinates of the *Acacia* specimens associated with the extracted soil type and the extracted vegetation type, they could both be mapped.

Finally, we illustrated how information about species other than the collected specimens may be obtained from herbarium labels, using the widespread mopane tree, *Colophospermum mopane* (Benth.) Léonard, as an example. First, we extracted locality records for *C. mopane* from the Global Biodiversity Information Facility (GBIF; www.gbif.org), as this is a data portal that is widely used for plotting species distributions at large spatial scales, and plotted these locality records. We then additionally extracted all localities where *Acacia* specimens were recorded to be growing in association with *C. mopane* from the *Acacia* database by searching the label information of the database for '*Colophospermum*' and '*mopane*'.

3. Results and discussion

Probably the best-known 'secondary' purpose of herbaria is to better understand the geographic distributions of species (Pyke and Ehrlich, 2010). Because localities and dates of collection are usually provided on herbarium labels, it is possible to map the distribution of species in space and time. This is especially valuable across large geographic areas, which may otherwise be difficult to survey (e.g. Hassan and Styles, 1990; Holmgren and Poorter, 2007; Platts et al., 2010; Greve et al., 2012; Marshall et al., 2012). Indeed, herbarium records are of growing importance as foundation evidence in global assessments such as IUCN RED listing (e.g. IUCN Standards and Petitions Subcommittee, 2014) and the emerging Intergovernmental Platform on Biodiversity and Ecosystem Services (IPBES) Initiative. Originally, mapping was limited to the individual localities where specimens had been collected (i.e.

producing "dot-maps", e.g. Fig. 1a). This has been used to, for example, identify regions of high diversity and thus conservation concern (e.g. Kreft and Jetz, 2007) or evaluate the contribution of protected areas to conserving biodiversity (e.g. Wieringa and Sosef, 2011).

With the development of large-scale environmental datasets such as climate and remote sensing datasets, species distribution models have increasingly been used to map contiguous species distributions (e.g. Blach-Overgaard et al., 2010; Marshall et al., 2012) based on the relationship between species occurrences and environmental factors such as climate, land use and soil (Guisan and Zimmermann, 2000). Species distribution models built on locality records also provide the basis for predicting how species will respond to expected changes in their environment, such as climate change or habitat loss and degradation (e.g. Cuni Sanchez et al., 2011). As an illustration we modelled the current and, under a given climate scenario, predicted future distribution of

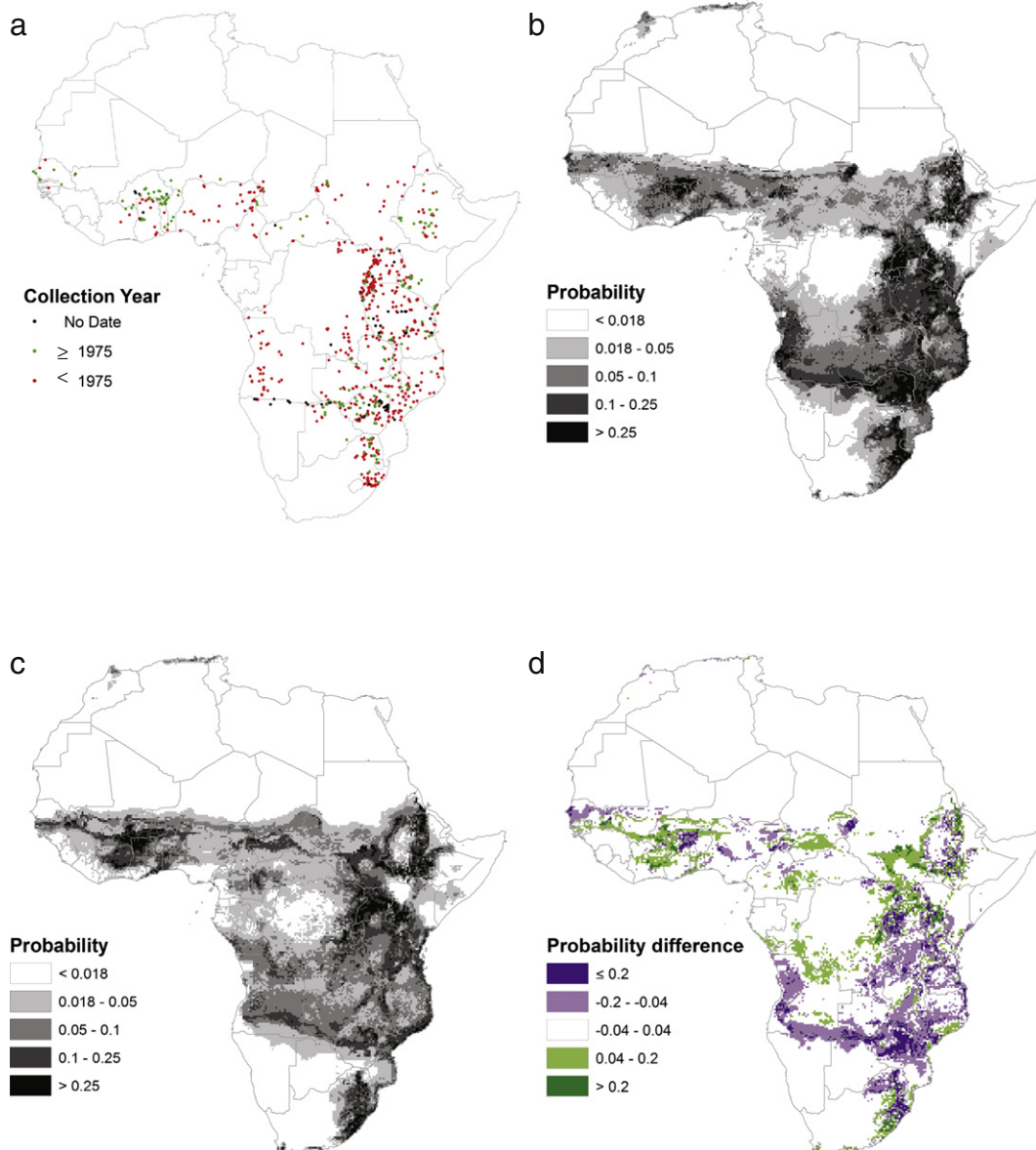


Fig. 1. *Acacia sieberiana* is mapped at an African scale from georeferenced locality data on herbarium labels (a). Collections from prior to 1975, from 1975 onwards and with an unknown date are indicated. Using boosted regression tree modelling, the distribution of *A. sieberiana* under current climate (b) and as predicted for 2080 (c) by the UKMO-HadCM3 model under an A1B scenario (IPCC, 2007) is also shown. The legend stipulates the probabilities with which the species has been predicted by a boosted regression tree model (b and c). The AUC value of the cross-validated models was 0.888, which is considered to be good (Elith, 2000). The difference between the probability of occurrence for future and current distributions is shown in (d): green areas represent regions where *A. sieberiana* is more likely to occur in the future than currently, and purple areas regions where the ranges of the species may be threatened as the climate becomes less favourable for the species.

A. sieberiana across Africa (Fig. 1b–c). In addition to showing the current and predicted future distribution of the species, we could highlight areas where conditions are expected to become more or less suitable for the species in the future (Fig. 1d). Thus, mapping species from herbarium records allows us not only to understand the biogeography of species, but also to assess the threats they face under a variety of scenarios.

Because collectors often provide additional information about the plant and its environment on herbarium labels (e.g. for *A. sieberiana* in our database approximately 60% of label records contained such information), such collections inform not only about geographic variation of the collected species, but potentially also of species characteristics and the environment in which specimens were collected (Pyke and Ehrlich, 2010). For example, we used the *Acacia* database to illustrate

how information about the distribution of a plant trait, namely tree height, can be derived from herbarium labels. Tree height, which is an elemental aspect of tree architecture and of great ecological consequence for the plant (Westoby, 1998; Archibald and Bond, 2003), is one trait that is often reported on herbarium labels. Here, we mapped the mean recorded height of *A. sieberiana* across its distribution range in Africa (Fig. 2a). Tree height represents a trait which might respond to climate change or human disturbances such as frequent fires or wood collection (Foden, 2002). Historical herbarium data of this trait might thus, for example, serve as a baseline for changes in functional traits over time.

Geographic variation in phenology related to, for example, flowering and fruiting can be gleaned from specimen labels or specimens

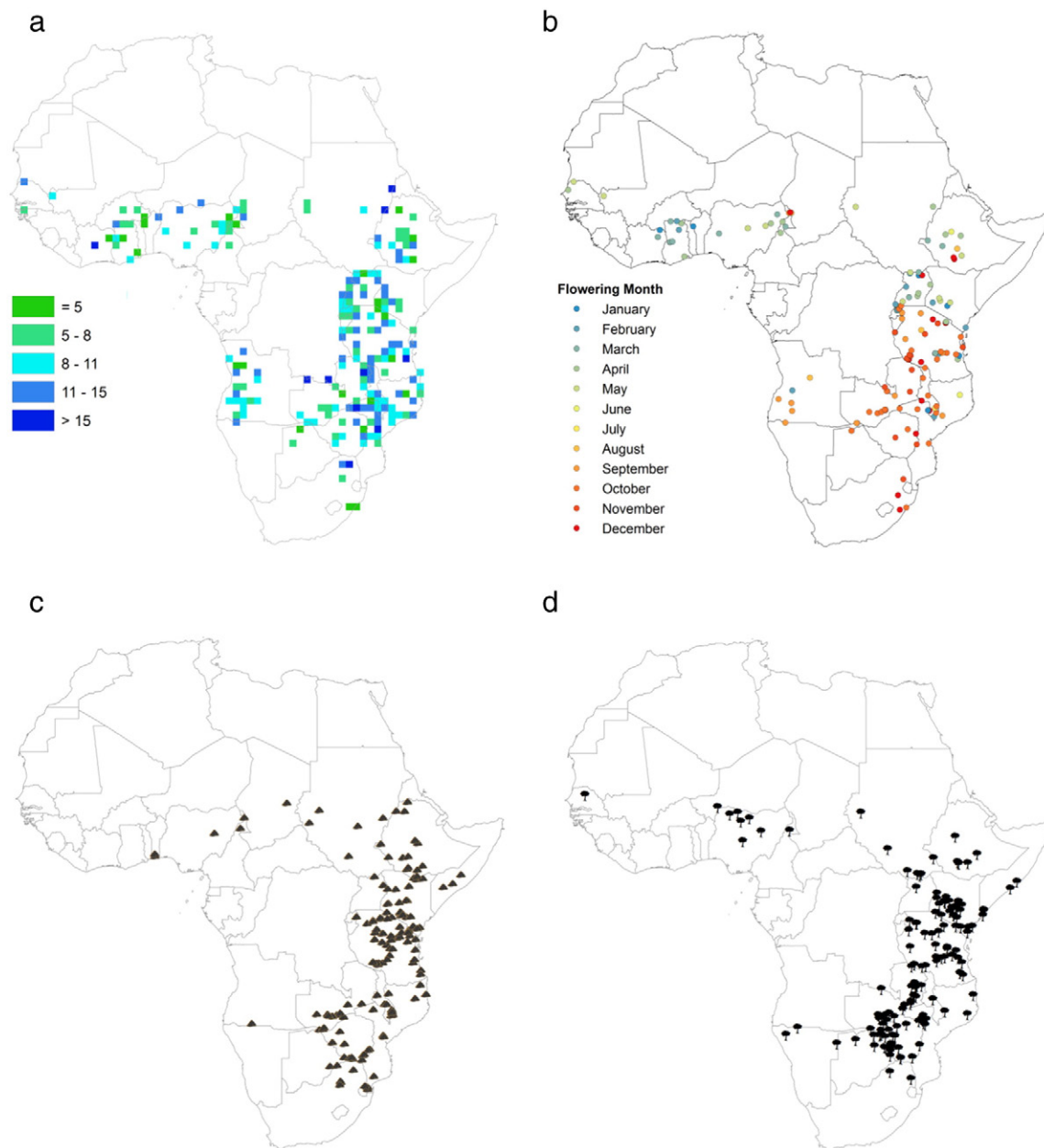


Fig. 2. Herbarium specimens can be used to map species traits and information about the environment. The mean height of *Acacia sieberiana* in each degree unit according to herbarium labels (a), and variation in the timing of flowering of *Acacia sieberiana* across the African continent (b) is shown. In addition, locality records of vertisol soils (c) and *Combretum* woodlands (d) from information on the herbarium labels of *Acacia* specimens are mapped. *Combretum* woodlands were classified as such if defined as *Combretum* woodlands/bushlands, or if *Combretum* species were mentioned as one of at the most three dominant tree species at a locality.

themselves (Proença et al., 2012). Here we show how the flowering phenology of *A. sieberiana* varies across its range (Fig. 2b), with southern trees flowering in the early austral summer, while east and west African trees flower earlier in the year. (This is partially consistent with subspecies designation; Appendix A, Fig. S1.)

Herbarium labels also have the potential to provide information about the distribution of various environmental factors associated with the collections, also at large spatial scales. As an example, we mapped both a soil type, namely vertisols, and the distribution of a major vegetation type – *Combretum* woodlands (Fig. 2c–d) from the *Acacia* database. The maps of vertisol and *Combretum* woodland distributions are by no means complete – they depend on where collections were made, and on whether collectors had the habit of recording these characteristics; they do, however, have the potential to augment existing data sources, and be interpolated to produce contiguous maps. Knowledge of the distribution of such environmental factors is not only valuable for e.g. assessing conservation status of soils and vegetation types, but can also be valuable for mapping taxa associated with them – in the present and the future (e.g. Preston et al., 2008). In addition, site details such as soils and altitudes can also help in matching sites where seed could be successfully planted in restoration or plantation programmes.

Additionally, information about species other than the collected specimens may be obtained from herbarium labels. *Colophospermum mopane* is widely distributed across the northern regions of southern Africa. However, a search for the species on GBIF produces a map of localities restricted mainly to South Africa, Botswana and Namibia, which are floristically better sampled and databased, while collections of the species from the important north-eastern regions of its distribution are either not databased, or the species is undersampled in the region

(Fig. 3). On the other hand, the *C. mopane*-associated records from the *Acacia* herbarium records provide several additional known localities for *C. mopane* in Zimbabwe, Zambia and Mozambique particularly, where GBIF records of the species are scarce (Fig. 3). Such methods of gaining distributions for associated species from herbarium labels are mainly useful for species that dominate vegetation or are conspicuous, and are easily identifiable (to ensure observer reliability in the absence of voucher specimens).

Finally, it should be mentioned that some regions of the world have been poorly inventoried in terms of biodiversity and ecology and, in some cases, are rarely revisited by botanists due to logistical or political reasons. The collections of *A. sieberiana* illustrate this for Angola, which was engaged in a civil war for many years. Most Angolan *Acacia* herbarium specimens of this species were collected prior to 1975, with most areas unsurveyed since this date (Fig. 1a). Herbarium specimens can be an invaluable (and sometimes only) source of biodiversity information for such regions. However, even in areas that have been more recently studied, basic biodiversity information is often missing, and herbarium data can fill some of these gaps, as shown above.

3.1. Temporal information

While we have focussed on the spatial applicability of herbarium specimens, they also have extensive uses for monitoring temporal changes in the environment. Mapping herbarium records in time has been explored less, particularly in Africa (Cherry, 2009). Yet, because herbarium specimens are dated, there is great potential to better explore temporal trends in biodiversity. Mapping changes over time is especially pressing in the face of extensive global change affecting biodiversity and society (IPCC, 2014). One expected consequence of climate

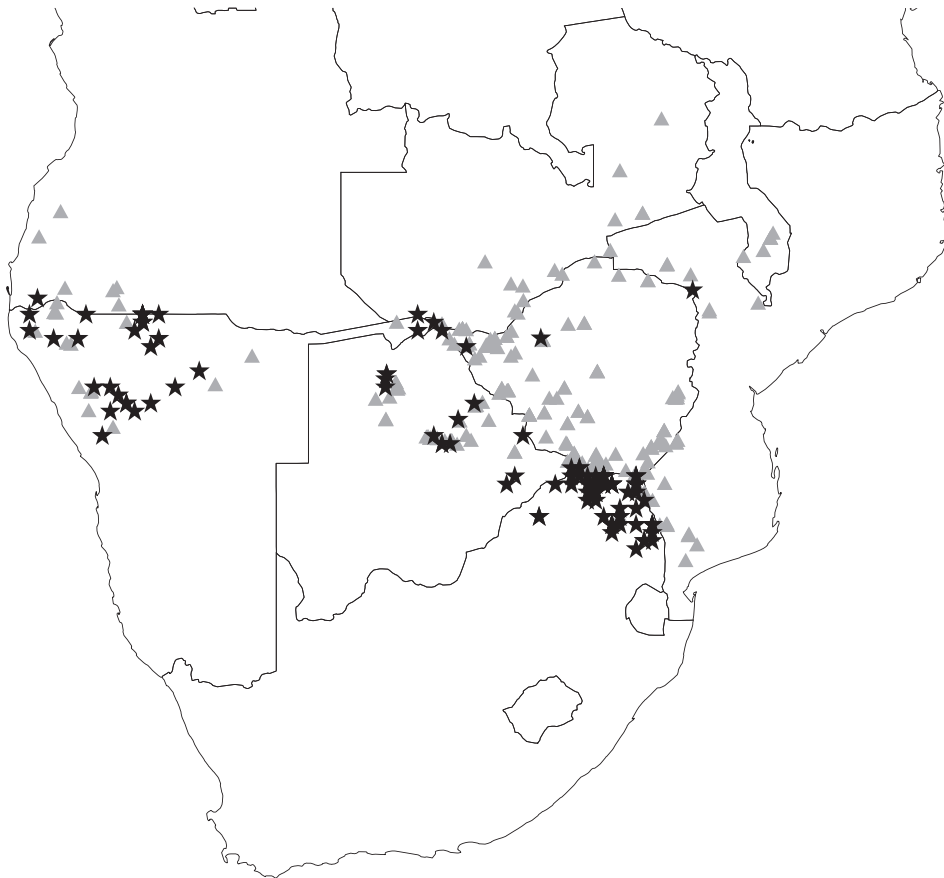


Fig. 3. Map of the northern regions of southern Africa showing localities of *Colophospermum mopane* obtained from the Global Biodiversity Information Facility (black stars), and from label information of *Acacia* herbarium specimens (grey triangles).

change is that species ranges will shift to track changing climate (Staudinger et al., 2012). In an African example, Wittig et al. (2007) use herbarium specimens to illustrate how the distributions of Sahelian species have changed over time: their ranges have shifted southwards since the 1970s as the region has become drier, indicating tracking of climate. Herbarium specimens, along with other data sources, have also been used to reveal changes in species composition due to agricultural activities around Mount Kenya (Kindt et al., 2007).

Herbarium specimens have also been used to track temporal changes in the phenological traits of species. Changes in the phenology of some species are of particular concern, as it might result in mismatches between the phenology of these species and other species with which they interact, e.g. between the flowering period of plants and their pollinators (Staudinger et al., 2012). Indeed, several studies have shown earlier onset of flowering in recent years that correspond to changes in climate (Sparks, 2007; Rawal et al., 2015).

Pauw and Hawkins (2011) cleverly employed herbarium specimens from an orchid group to highlight the population decline of their associated pollinator: a bee species. The pollinarium of these orchids breaks off during pollination. The authors recorded the proportion of the flowers of herbarium specimens that had lost their pollinarium, and could thereby show a decrease in pollination incidence, and thus bee populations, over time.

4. Synthesis

The examples above summarise possible uses of herbarium records for gathering a variety of information about collected species, their associated species and their general environment. Accessing this information is becoming increasingly feasible as herbaria are digitized and their data become available through shared portals such as the GBIF. Possible shortcomings (e.g. collection biases, data inaccuracies and unverifiability) of using herbarium specimens for purposes for which they were not originally collected should be considered to ensure data reliability (see Appendix A). Nevertheless, the value of herbarium specimens for conservation should not be underestimated. In order to conserve populations, species and ecosystems, we need to understand their distributions, characteristics and environments – all information that can be gleaned from herbarium labels. Thanks to good practices in specimen cataloguing, herbarium data can be used for obtaining a variety of information about species, their environments and changes over time. Indeed, one of the challenges facing conservation today is a lack of knowledge of the trends, status and functional roles of many taxa (Rands et al., 2010). Herbarium specimens (and other biological collections) have the potential to fill some of these knowledge gaps – both about the recent past and the present. They are particularly valuable in regions that have received less scientific interest (which are often also regions with high diversity), including many parts of Africa. Thus, as herbarium specimens provide knowledge about species and their ecosystems, they provide essential baseline knowledge for conservation biology. It is thus essential to ensure 1) the continued support of herbaria and their staff so that biological specimens continue to be available into the future, as new uses for them are found; 2) that specimens continue being added to herbaria so that trends in space and time can be elucidated; 3) that herbarium data are databased accurately along with all the specimen-associated field notes, and 4) that herbarium specimens are correctly named and that names in databases are updated where necessary to reflect any changes in specimen identification. That way, conservationists will continue to gain from the rich resources available in herbaria.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at <http://dx.doi.org/10.1016/j.sajb.2016.03.017>.

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