




# Developing an initial inventory of non-native invasive plants based on roadside surveys: recent experience in southern and eastern Africa

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**Background:** Lists of non-native invasive species are needed for the development of strategies and plans to control them.

**Objectives:** This paper describes the development of an initial inventory of non-native plants based on roadside surveys, and reviews the advantages and challenges associated with the methodology.

**Methods:** We conducted surveys in 11 southern and eastern African countries and listed the presence of non-native plants at just under 107 000 roadside localities between 2008 and 2019. Localities were georeferenced and used to create a database of the distribution of 708 non-native plant species.

**Results:** The survey effort varied between countries, with sampling taking place fairly comprehensively in smaller countries (e.g., Eswatini, Malawi and Rwanda were well covered, with >90% of half-degree grid cells reached), while coverage was acceptably high in Uganda, Kenya and Tanzania (78–49%). In other countries, coverage was less. The greatest number of non-native species was recorded in Kenya (430), followed by Tanzania (341), Malawi (313) and Zambia (240). The most frequently recorded species was *Lantana camara*, with 5 566 records, followed by *Senna siamea* (3 526), *Eucalyptus* spp. (3 409), *Ricinus communis* (3 261) and *Cascabela thevetia* (3 156). Our inventories made a significant contribution to the regional database, constituting 58% of all plant observations in GBIF across the 11 countries in 2018. Several field guides have been produced based on these lists, and they provide a useful resource where none existed until recently.

**Conclusion:** Alternative methods exist for the development of lists, including remote sensing and citizen science, and each has advantages and drawbacks. Roadside surveys are not comprehensive as they are limited to roadsides and subject to several potential biases because inconspicuous species are excluded, and observers have different levels of competence. We conclude nonetheless that roadside surveys, undertaken by experienced observers during the course of other duties that involve widespread travel, can provide a relatively inexpensive and very useful initial inventory, especially in lower- and middle-income countries where the capacity to conduct other survey options is lacking.

**Keywords:** biological invasions, inventories, mapping.

## Introduction

People have moved species to regions outside their natural range for centuries, and the rates of introduction of these so-called non-native species are increasing (IPBES 2023). Biological invasion is the process whereby non-native species establish themselves and spread in new ecosystems, often causing harm. Biological invasions contribute substantially to the impacts of global change, negatively

affecting crop and livestock production, human and animal health, biodiversity and the delivery of ecosystem services (IPBES 2023). Since 1992, 196 countries have ratified the Convention on Biological Diversity (CBD), which aims to conserve biodiversity, use it sustainably and share the benefits fairly. Article 8(h) of the CBD requires member countries to prevent, control or eradicate non-native species that threaten ecosystems, habitats or species. In December 2022, the Conference of the Parties to the CBD adopted the Kunming-Montreal Global Biodiversity Framework. Target 6 of this framework calls for parties to 'eradicate or control invasive non-native species, especially in priority sites' by 2030, and parties to the CBD are encouraged to produce a National Invasive Species Strategy and Action Plan. There is thus a clear intent to address this issue at a global scale.

Despite the commitment to managing biological invasions, many countries lack the resources to do so. In low- and middle-income countries, many of which are in Africa, there is often a lack of basic information on what species are present, where they occur, what impacts they have and how they should be managed. For example, a study in 2008 found that only 3.6% of all published papers on biological invasions were from Africa, with three quarters of them coming from a single country, South Africa (Pyšek et al. 2008). Di Marco et al. (2017) also found a strong geographical bias in studies in the field of conservation science in general, with 40% of global studies carried out in the USA, Australia or the UK, and only 10% and 6% respectively in Africa or Southeast Asia. In fact, several countries in Africa received no research attention at all.

Without a list of species and information on their distribution and known impacts it is near impossible to develop a comprehensive national strategy as required by the CBD. In addition, such information is needed to raise awareness, and to monitor trends in spread and the effectiveness of control. The detection of new introductions and determining their distribution is also important for the development and implementation of non-native plant management plans. Incomplete or poorly contextualised lists of non-native species pose a biosecurity risk and reduce the effectiveness of prevention and control strategies (Kolar & Lodge 2001).

Although there have been attempts to develop lists, many are a poor reflection of the actual status of introduced plants, especially in poorer countries. The number of documented species was often significantly underestimated in such countries due to a lack of resources and capacity to undertake regular surveys (McGeoch et al. 2010). Of the ten errors in invasive non-native listings, most can be attributed to a lack of knowledge or measurement error (McGeoch et al. 2012). Other errors include human error; incomplete information searches; species identification; survey information on presence, extent and population

dynamics outside of indigenous range; resolution of data and scaling of 'non-native range'; data and knowledge not documented; documented data and knowledge not readily or widely accessible; baseline information on indigenous range; and research on biodiversity impact. A major challenge is that apparent increases in the number and range of invasive non-native species is due to increases in monitoring and recording efforts and not necessarily real increases, especially in understudied areas (Caley et al. 2008).

There has been a concerted effort to address some of these uncertainties when developing inventories of non-native invasive species, and global databases often offer open access to increase their use. These include the CABI Distribution Database and the Invasive Species Compendium (CABI 2025), the Global Invasive Species Database of the IUCN Invasive Species Specialist Group (ISSG 2015), and the Global Register of Introduced and Invasive Species, which has information on non-native invasive species for 196 countries (Pagad et al. 2022). However, these resources are often largely dependent on information sourced from peer-reviewed publications, and these are often lacking in lower- and middle-income countries. Africa, outside of South Africa, has a limited number of publications or information resources on biological invasions. Other sources of information on the presence and distribution of invasive non-native plants in Africa include Rejmánek et al. (2017) for Angola; Maroyi (2012, 2022) for Zimbabwe; Borokini et al. (2023) for Nigeria; Tiebre et al. (2024) for Ivory Coast; the Usambara Mountains, Tanzania (Dawson et al. 2008; Sheil 2008); and protected areas in Uganda (Rejmánek 1996) and West Africa (IUCN/PACO 2013). Many others mainly focus on agricultural weeds, e.g. Bogdan (1950, 1965), Terry (1984), Ivens (1967) and Terry & Michieka (1987) for East Africa; Germain (1952), Mullenders (1954), Schmitz (1971), Mosango (1983a, 1983b) and Lubini (1986) for Central Africa; Wild (1955) and Drummond (1984) for Zimbabwe and El Hadidi et al. (1996) for Egypt. Many of these lists are incomplete as highlighted by McGeoch et al. (2012).

To address some of these shortcomings McGeoch et al. (2012) suggested that there be ongoing and expanded investment in research and monitoring; support for regional and global efforts to improve information accessibility; adoption of measures to improve the transparency, repeatability and communication of listing methods; and improving the procedures for expert contributions in the process. To address some of these concerns one of us (ABRW) undertook extensive roadside surveys in eastern and southern Africa to develop an inventory of non-native plants and their distribution, a need repeatedly expressed by several countries (Boy & Witt 2013; Witt & Luke 2017).

Roadside surveys are one of many possible ways to develop lists of invasive non-native species, and they have

**Table 1.** Advantages and disadvantages associated with roadside surveys of non-native invasive species at a national or regional level

Advantages	Disadvantages
<ul style="list-style-type: none"> <li>• Can be carried out opportunistically, therefore cost-effective.</li> <li>• Can cover large areas.</li> <li>• Populations can be classified into invasion status categories (present, established, invasive).</li> <li>• Linear spread can be monitored (expanding, stable, contracting).</li> <li>• Provides an important input to the development of national inventories.</li> </ul>	<ul style="list-style-type: none"> <li>• Requires experienced observers.</li> <li>• Limited to road networks, which can be sparse.</li> <li>• Limited to roadsides and adjacent areas.</li> <li>• Biased towards larger, conspicuous growth forms.</li> <li>• Not effective at monitoring changes in cover away from roadsides.</li> <li>• Security concerns in politically unstable areas.</li> </ul>

both advantages and disadvantages (Table 1). As a result, they cannot be used as the only source of data to develop comprehensive lists at national or regional scales. Other methodologies include monitoring plots, citizen science (e.g., iNaturalist), and drone and satellite remote sensing, but all these also have advantages and disadvantages.

Monitoring at a smaller scale can be undertaken by simply walking through plots or along transects. Walked surveys provide a detailed assessment of species present but generally only cover small areas. Urban centres lend themselves to walked surveys and are an easy and effective way of determining what is present in a town or city. Urban areas are often also where non-native species first establish and become invasive, making them the ideal area to detect emerging weeds (see, for example, Milton & Dean [2025]). McLean et al. (2018) used the roads in a town as transects, recording non-native plants in gardens, agricultural areas, industrial areas and urban green spaces. Despite being effective in detecting non-native species, the survey was time-consuming and required a high level of taxonomic expertise (McLean et al. 2018). Walking obviously also allows for access to areas largely inaccessible to vehicles, such as along walking trails, which are often a pathway for invasive non-native species (Wells et al. 2012; Liedtke et al. 2020). Longer distances, depending on the type of terrain, can be surveyed using bicycles or motorbikes. Although these modes of transport offer accessibility to more areas than motor cars, they are generally not suitable for covering large areas.

Citizen science is becoming an increasingly popular source of biodiversity information (Fink et al. 2014; Chandler et al. 2017). For example, 87% of the participants in surveys in Germany are volunteers (Schmeller et al. 2009). It is estimated that more than 50% of the data in the Global Biodiversity Information Facility (GBIF) comes from citizen science platforms (Chandler et al. 2017), and that this is likely to increase. The quality of much of this data has however been questioned (Kosmala et al. 2016; Bayraktarov et al. 2019), resulting in a barrier to their use (Burgess et al. 2017). There is a perceived lack of data accuracy, which is why citizen science is challenged or mistrusted (Aceves-Bueno et

al. 2017; Fraisl et al. 2022). In New Zealand, the public contributes significantly to the number of reports of non-native species, but confidence is low because of high false positive rates compared to other (professional) data providers (see Pocock et al. 2024).

A lack of structure, training and protocols in most citizen science projects is also concerning (Bowler et al. 2022). In unstructured projects, observers make independent decisions, and this creates heterogeneity in the data (Isaac & Pocock 2015; Boakes et al. 2016; August et al. 2020). Species occurrence records are also not accompanied by any information about sampling methods (Di Cecco et al. 2021). In addition, common species are often under-reported by citizen scientists, and rare species are often over-reported (Snall et al. 2011; Kamp et al. 2016; Troudet et al. 2017; Johansson et al. 2020). As a result, there are often fewer specimens of widespread and abundant species in herbaria (ABRW, pers. obs.). Citizen scientists were also less likely to report the presence of a species from a specific locality, if it had been reported from that site before (Bowler et al. 2022). This information is important when mapping changes in distribution.

Most citizen scientists, at least in Germany, commonly look for species in open habitats, such as wetlands, water bodies and meadows, and less often in urban and agricultural areas (Bowler et al. 2022). Agricultural areas are typically underrepresented (Bowler et al. 2022), and this has implications because invasive non-native plants readily establish and grow in disturbed settings. Despite these and other issues, many can be addressed, and citizen science is an opportunity to gather information in a cost-effective manner.

Despite the valuable contribution that citizen science makes to our understanding of biodiversity in many countries around the world, this is not the case in Africa. The global contribution of Africa to over 60 million records on GBIF is only 2.7%. Most African records were also for animals, and plants only made up 14.9% of the records (Ganglo 2023), and South Africa contributed more than 50% of the data for Africa (Ganglo 2023). In addition, 17% of the plant records were not determined to the species level. The major challenge

in acquiring data was the lack of road access (Ganglo 2023), which contributes to inventory completeness (Ganglo & Kakpo 2016; Troudet et al. 2017). This is clearly a major challenge in developing inventories in countries with poor road infrastructure.

Remote sensing has been widely used in the recent past for detecting, mapping and monitoring invasive non-native plant species, and is especially useful in determining the presence of species in inaccessible areas (Joshi et al. 2004; Asner et al. 2008; Huang & Asner 2009; Bradley 2014; Peerbhay et al. 2016). This technology has been successfully applied to map the distribution of several plant and animal species (Joshi et al. 2004), being less resource intensive and faster than traditional methods (Underwood et al. 2003). However, to detect an invasive non-native plant species with remote sensing, the target species must have a unique spectral, textural or phenological signal distinguishing it from other species (Bradley 2014). The ability to differentiate between species is further complicated by chlorophyll content, leaf pigment and leaf senescence timing (Rakgoale & Ngetar 2024). The species needs to have relatively high percentage cover to be detected, and many satellites have insufficient spectral, temporal or spatial resolutions to be of any value even in the detection of single species within native vegetation. Remote sensing is very useful for mapping the distribution and spread of known invasive non-native species, but it is not effective for identifying several invasive non-native species within a landscape, especially if they are unknown and have no identifiable spectral reflectance. In addition, although much satellite imagery is freely available, the high-resolution images required to map non-native species are costly (Sladonja et al. 2022).

While the use of satellites in environmental biology has stabilised since 2013, the use of drones has steadily increased in the last two decades (Nowak et al. 2018). Images acquired from drones are very effective for monitoring invasive plant species and are extremely practical for use in large or inaccessible areas (Sladonja et al. 2022). Drones also provide an opportunity to monitor changes in particular sites, without the bias associated with other methodologies, such as roadside surveys undertaken by a host of different observers. A comparative trial between ground and drone-based mapping found that it took significantly less time to cover the same area using a drone, and that drone data could easily be re-used as precision was high (Sladonja et al. 2022). On the downside, drone mapping costs are high and there is a need for experts to fly the drone and do the data analysis. Also, it is highly unlikely that drones will detect uncommon species, or low growing herbs. Although these can also be missed during roadside surveys, they can easily be detected and identified by undertaking regular stops.

In South Africa, a reasonably comprehensive list of non-native plants, mainly established non-native and invasive species, and their distribution, was developed

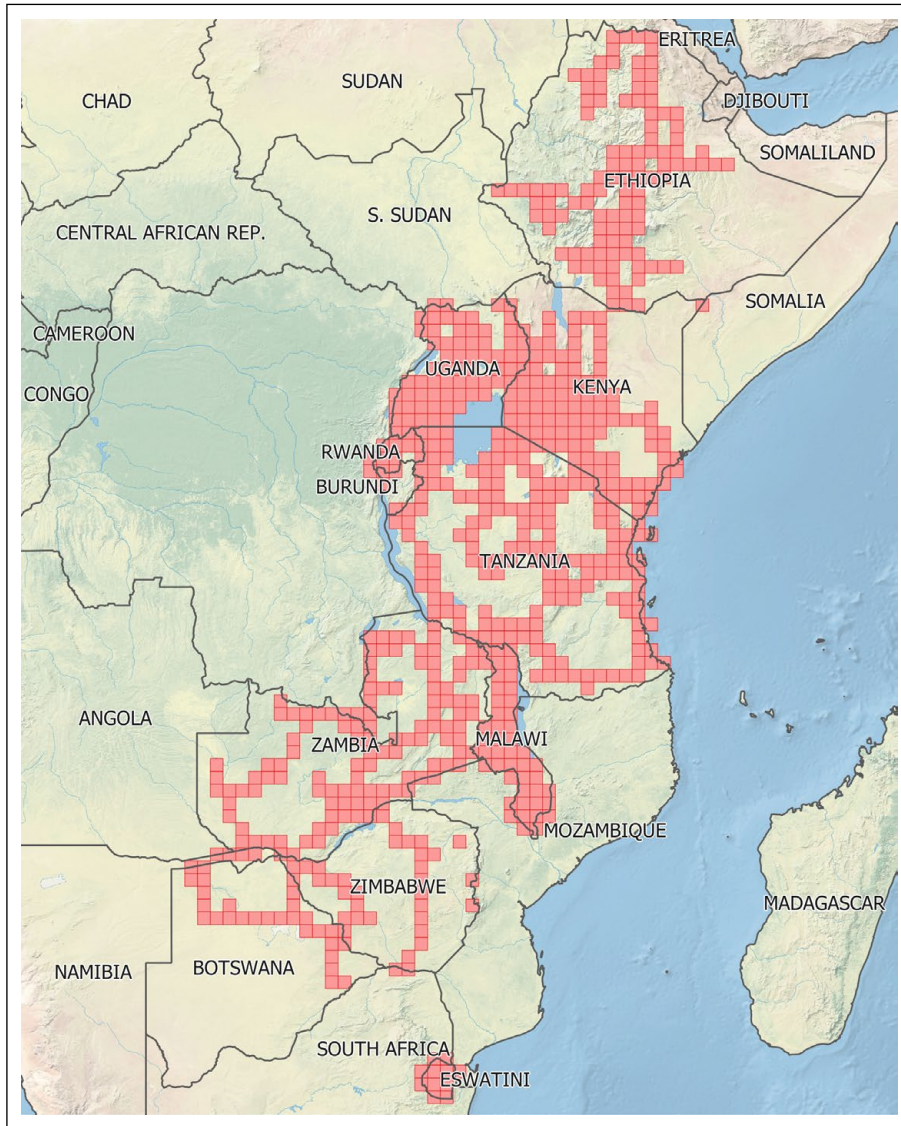
over 30 years by recording them in roadside surveys (Henderson 2007, 2020). After moving to Kenya in 2007, ABRW was required to travel extensively throughout southern and eastern Africa and used the opportunity to record the presence of non-native plant species with a focus on those that were non-native, invasive or potentially invasive. In this paper, we describe the development of a preliminary inventory for 11 African countries based on roadside surveys.

## Methods

The surveys reported here were conducted in 11 African countries, where the presence of non-native plants along roadsides was recorded at just under 107 000 localities between 2008 and 2019. The coverage varied (e.g., all of Eswatini was surveyed over 7 days in 2016, while parts of Kenya were surveyed, some multiple times between 2008 and 2016). Survey efforts were usually rapid, i.e. lasting a few days to three weeks per survey when funding became available, or when opportunities to travel arose. Surveys in Ethiopia, Kenya, Malawi, Tanzania, Uganda and Rwanda were mostly funded, but additional surveys were largely opportunistic, undertaken during vacations, or on road trips to project sites, conferences, workshops or meetings. Most roads were only surveyed once, especially those outside of eastern Africa. Where possible, the same roads were surveyed more than once, and preferentially during spring or summer when plants were actively growing and/or flowering. Surveys were conducted by the lead author (ABRW) who also drove the vehicle. Considerable distances were covered, generally travelling at <60 km/hour depending on the road conditions, covering tens of thousands of kilometres (Figure 1).

We recorded the location of non-native species using a handheld global positioning system. When a specimen was located, information pertaining to it was recorded. If other non-native species were visible at the same locality, they were added as records to that particular locality. Established non-native or invasive non-native species that could not be identified in the field were collected or photographed for later identification by consulting field guides, taxonomists or other resources.

Grass species, except for the conspicuous ones such as *Cenchrus setaceus* and *Arundo donax*, were not recorded during surveys as they are difficult to identify from a moving vehicle. The presence of roadside or agricultural weeds, especially herbs, many of which are introduced (e.g., *Bidens pilosa*, *Erigeron bonariensis* [= *Coinya bonariensis*], *Tribulus terrestris* and *Sida* spp.), were not consistently recorded because they are not known to have a significant impact on biodiversity or livestock production in Africa. Crop species, other than those known to be established or invasive (e.g., *Psidium*



**Figure 1.** Eastern and southern Africa showing the half degree grid cells (approx.  $55 \times 55$  km) in eleven countries in which non-native plants were recorded during roadside surveys between 2008 and 2019.

*guajava*) were generally also not recorded. Non-native species other than crops that were not established or invasive and could not be immediately identified were also not recorded. However, we recorded those species that we were familiar with, and which had been recorded as invasive elsewhere in Africa even if they were not established or invasive in the area being surveyed. For example, species such as *Jacaranda mimosifolia* and *Delonix regia* were recorded in eastern Africa despite not being invasive there but because they are highly invasive in South Africa and Ghana, respectively.

Data were recorded in a logbook and later entered into a spreadsheet. These data were cleaned and aligned to common vocabularies. CABI Thesaurus was used as a taxonomic reference (<https://www.cabidigitallibrary.org/cabi-thesaurus>). Other information was added or aligned to the Darwin Core standards for biological information, which enabled interoperability with the Global Biodiversity Information Facility (GBIF). Many records were then uploaded to the GBIF website, funds allowing, and included in CABI's Invasive Species Compendium

distribution tables and maps once the data had been published. Data were also made available for inclusion in the Global Register of Introduced and Invasive Species.

The records were also used to develop distribution maps by summarising them by grid cells measuring 0.5 degrees of longitude and 0.5 degrees of latitude for each country (grid cells of  $\sim 55 \times 55$  km). This information was included in various field guides together with colour images and other information (Table 2).

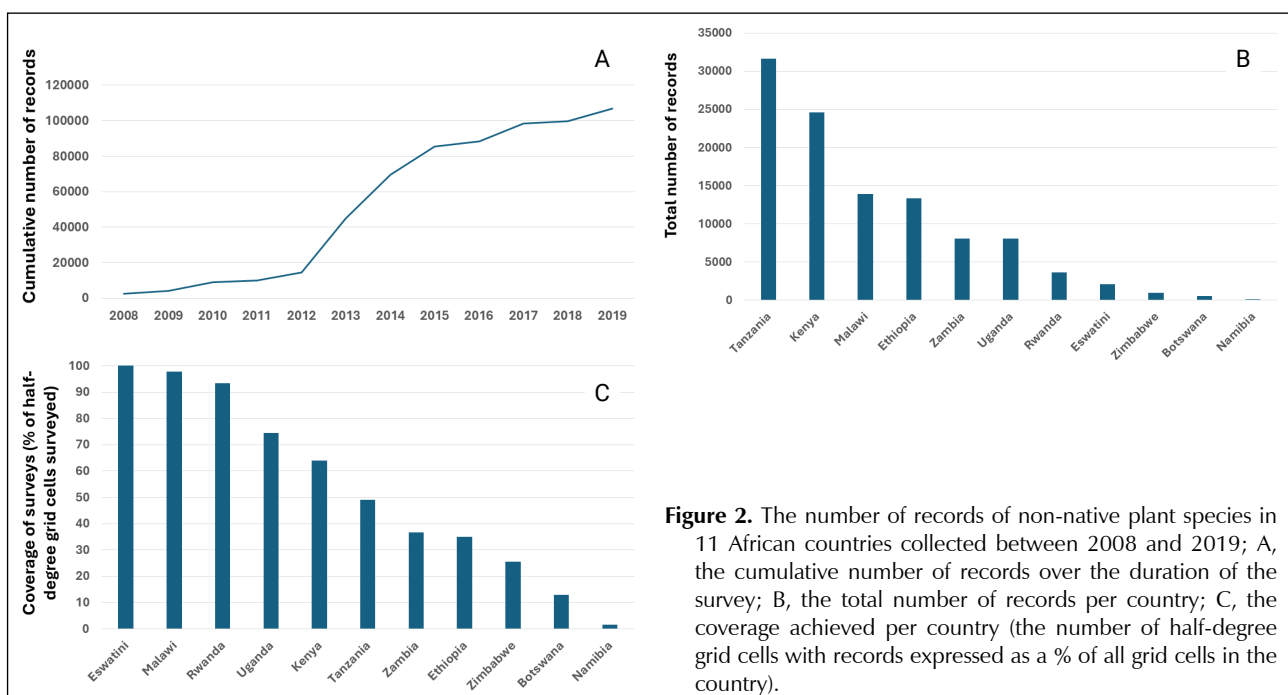
## Results

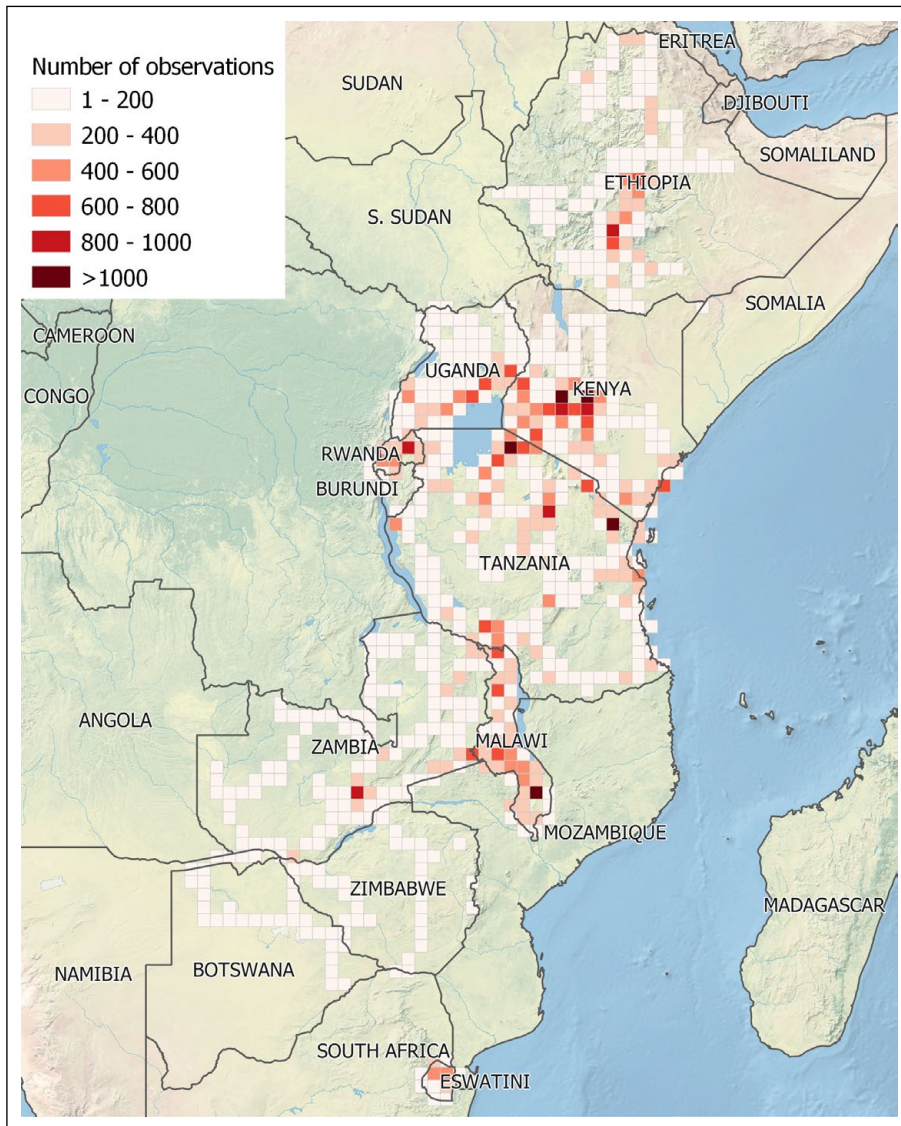
### Records of non-native species

We assembled 106 928 records of non-native plants over 11 years during our surveys (Figure 2A), which covered between <1% (for Namibia) to 100% (for Eswatini) of half degree grid cells in each country (Figure 2B). Of the 11 countries surveyed, Eswatini, Malawi and Rwanda

**Table 2.** Publications that were generated based on roadside surveys in 11 African countries, in chronological order of date of publication

Product	Coverage	Content	Reference
Scientific paper	Ethiopia, Kenya, Rwanda, Tanzania, Uganda	Distribution of <i>Chromolaena odorata</i> and its socio-economic impacts in northern Tanzania	Shackleton et al. (2017b)
Book	Ethiopia, Kenya, Rwanda, Tanzania, Uganda	Field guide to established and invasive non-native plants	Witt & Luke (2017)
Scientific paper	Ethiopia, Kenya, Rwanda, Tanzania, Uganda	Distribution of <i>Lantana camara</i> and its socio-economic impacts in Uganda	Shackleton et al. (2017a)
Scientific paper	Ethiopia, Kenya, Rwanda, Tanzania, Uganda	Distribution of <i>Opuntia stricta</i> with additional information on local perceptions of <i>O. stricta</i> in Laikipia County, Kenya	Shackleton et al. (2017c)
Book	Laikipia County, Kenya	Field guide to established and invasive non-native plants	Witt (2017)
Scientific paper	Serengeti-Mara ecosystem, Kenya and Tanzania	A preliminary list of non-native plant species and discusses potential impacts of six high-risk species	Witt et al. (2017)
Scientific paper	Ethiopia, Kenya, Rwanda, Tanzania, Uganda	Data on the distribution and potential ecological impacts of invasive non-native plant species	Witt et al. (2018)
Scientific paper	Botswana, Burundi, Eswatini, Ethiopia, Kenya, Malawi, Mozambique, Rwanda, Tanzania, Uganda, Zambia, Zimbabwe	Distribution of <i>Tithonia</i> species and the socio-ecological impacts of <i>T. diversifolia</i> in Zambia	Witt et al. (2019)
Scientific paper	Eastern and southern Africa	Distribution of <i>Mimosa diplotricha</i> and its socio-economic impacts in Malawi	Witt et al. (2020a)
Scientific paper	Eastern and southern Africa	Distribution and impacts of <i>Mimosa pigra</i> and its socio-economic impacts in Zambia	Witt et al. (2020b)
Scientific paper	Laikipia County, Kenya	Distribution and impacts of invasive non-native plants	Witt et al. (2020c)
Book	Malawi, Zambia	Field guide to established and invasive non-native plants	Witt et al. (2024)

**Figure 2.** The number of records of non-native plant species in 11 African countries collected between 2008 and 2019; A, the cumulative number of records over the duration of the survey; B, the total number of records per country; C, the coverage achieved per country (the number of half-degree grid cells with records expressed as a % of all grid cells in the country).

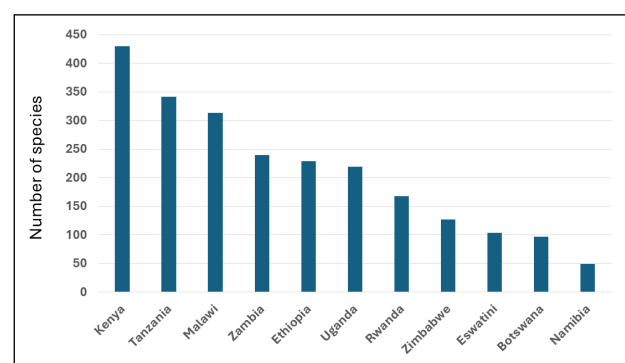


**Figure 3.** Survey effort, i.e., the number of records of non-native species associated with grid cells ( $\sim 55 \times 55$  km) in 11 countries in eastern and southern Africa surveyed between 2008 and 2019.

were well covered (>90%), followed by Uganda, Kenya and Tanzania (78–49%, Figure 2C). Kenya, despite being a large country, was quite well covered because the surveyor (ABRW) resided in that country, while other countries were less well surveyed because of fewer opportunities, limited road infrastructure, and security concerns in the case of Ethiopia. In total, surveys between 2008 and 2019 resulted in the identification and recording of 708 non-native plant species. The number of records per grid cell ( $\sim 55 \times 55$  km) varied significantly with species being recorded at over 1 000 localities within some grid cells, suggesting possible multiple duplicate records (Figure 3). These were often associated with major urban centres, where non-native plants, especially ornamentals, are common in gardens, public open spaces and roadsides. However, it could also reflect a survey bias in that more time was spent in urban centres undertaking surveys, especially when attending workshops, conferences or meetings; ABRW also resided in Nairobi, Kenya, which contributed to more records for this city. Consequently, there were few survey hotspots, especially in Zimbabwe and Botswana, where

surveys were undertaken while in transit and almost no time was spent in urban centres.

The greatest number of non-native species were recorded in Kenya (430), followed by Tanzania (341), Malawi (313) and Zambia (240) (Figure 4). The most frequently



**Figure 4.** The number of non-native plant species recorded per country during roadside surveys in 11 African countries between 2008 and 2019.

recorded species was *Lantana camara*, with 5 566 records, followed by *Senna siamea* (3 526), *Eucalyptus* spp. (3 409), *Ricinus communis* (3 261) and *Cascabela*

*thevetia* (3 155) (Table 3). The most frequently recorded species were shrubs or trees (Table 3), possibly because they were more conspicuous than herbs.

**Table 3.** Species that were recorded >1 000 times during roadside surveys in eastern and southern Africa between 2008 and 2019. An asterisk (\*) indicates that the origin of the species is uncertain or considered to be native to one or more of the countries surveyed

Species	Family	Growth form	Number of records
<i>Lantana camara</i> L.	Verbenaceae	Large shrub/climber	5 566
<i>Senna siamea</i> (Lam.) H.S.Irwin & Barneby	Fabaceae	Large tree	3 526
<i>Eucalyptus</i> spp.	Myrtaceae	Large tree	3 409
<i>Ricinus communis</i> L.*	Euphorbiaceae	Large shrub/small tree	3 261
<i>Cascabela thevetia</i> (L.) Lippold	Apocynaceae	Large shrub/small tree	3 155
<i>Solanum campylacanthum</i> Hochst. ex A.Rich.*	Solanaceae	Small shrub/herb	2 734
<i>Tithonia diversifolia</i> (Hemsl.) A.Gray	Asteraceae	Large shrub	2 655
<i>Agave sisalana</i> Perrine	Agavaceae	Small shrub	2 409
<i>Grevillea robusta</i> A.Cunn. ex R.Br.	Proteaceae	Large tree	2 310
<i>Leucaena leucocephala</i> (Lam.) de Wit	Fabaceae	Large shrub/small tree	2 252
<i>Jacaranda mimosifolia</i> D.Don.	Bignoniaceae	Large tree	1 988
<i>Bougainvillea</i> spp.	Nyctaginaceae	Large shrub/climber	1 955
<i>Senna spectabilis</i> (DC.) H.S.Irwin & Barneby	Fabaceae	Large tree	1 944
<i>Senna occidentalis</i> (L.) Link.	Fabaceae	Small shrub/herb	1 880
<i>Euphorbia tirucalli</i> L.*	Euphorbiaceae	Large shrub/small tree	1 843
<i>Azadirachta indica</i> A.Juss.	Meliaceae	Large tree	1 834
<i>Psidium guajava</i> L.	Myrtaceae	Small tree	1 821
<i>Parthenium hysterophorus</i> L.	Asteraceae	Herb	1 810
<i>Senna didymobotrya</i> (Fresen.) H.S.Irwin & Barneby	Fabaceae	Large shrub	1 563
<i>Datura stramonium</i> L.	Solanaceae	Herb	1 532
<i>Calotropis procera</i> (Aiton) W.T.Aiton*	Apocynaceae	Large shrub	1 480
<i>Delonix regia</i> (Bojer ex Hook.) Raf.	Fabaceae	Large tree	1 463
<i>Biancaea decapetala</i> (Roth) O.Deg. [= <i>Caesalpinia decapetala</i> (Roth) Alston]	Fabaceae	Large shrub/climber	1 459
<i>Duranta erecta</i> L.	Verbenaceae	Large shrub/small tree	1 446
<i>Melia azedarach</i> L.	Meliaceae	Large tree	1 433
<i>Mangifera indica</i> L.	Anacardiaceae	Large tree	1 335
<i>Opuntia stricta</i> (Haw.) Haw.	Cactaceae	Large shrub	1 258
<i>Gmelina arborea</i> Roxb. ex Sm.	Lamiaceae	Large tree	1 207
<i>Senna obtusifolia</i> (L.) H.S.Irwin & Barneby	Fabaceae	Small shrub	1 203
<i>Opuntia ficus-indica</i> (L.) Mill.	Cactaceae	Large shrub	1 193
<i>Catharanthus roseus</i> (L.) G. Don.	Apocynaceae	Small shrub/herb	1 133
<i>Agave americana</i> L.	Agavaceae	Small shrub	1 129
<i>Argemone</i> spp.	Papaveraceae	Herb	1 083
<i>Xanthium strumarium</i> L.	Asteraceae	Small shrub/herb	1 034
<i>Dovyalis afra</i> (Hook.f. & Harv.) Warb.*	Salicaceae	Large shrub/small tree	1 007

Data from these roadside surveys have made a significant contribution to our understanding of plant invasions in Africa. When published in GBIF in 2018, the roadside data described here represented 58% of all plant observations recorded in GBIF across the 11 surveyed countries. Currently (May 2025) the data still represents a significant proportion of the known status of plants in these countries, constituting 29% of all plant observations, despite our narrower focus on only invasive non-native species, and the roadside survey data are second only to iNaturalist records, which make up 33% of all plant observations. The dataset of roadside observations (partial or whole) has been cited 412 times in further studies, including 314 journal articles.

## Products arising from roadside surveys

To date, 12 publications (field guides and scientific analyses) have been published based on data in the inventories produced by roadside surveys covered in this paper (Table 2). There are two regional field guides, one covering detailed descriptions of 200 species in Ethiopia, Kenya, Rwanda, Tanzania and Uganda, and another that covers 138 species in Malawi and Zambia. Another field guide, focusing only on Laikipia County in Kenya identified 145 non-native plant species but only 45 species are described in detail. Several other publications on *Chromolaena odorata*, *Lantana camara*, *Mimosa diplotricha*, *M. pigra*, *Opuntia stricta* and *Tithonia* species included distribution data collected during surveys. A paper was also published listing 245 non-native species in the Serengeti–Mara ecosystem and discussing the potential threats that they pose in that important area. Another field guide that includes over 400 non-native plant species in South Africa (and Lesotho to a limited extent) was based on separate roadside surveys (Henderson 2020, not shown in Table 2). The South African field guide, and other surveys arising from the roadside surveys in that country, are not covered here. Although our surveys covered parts of Botswana and Zimbabwe, most of Eswatini, and a very small portion of Namibia, there are no known field guides or other publications covering established and invasive non-native species available for those countries yet. In addition to the publications listed in Table 2, a dataset of 77 000 non-native species observation records for plants in sub-Saharan Africa were added to GBIF records.

## Discussion

### The value of roadside surveys

Roadside surveys have produced a valuable record of non-native plant richness and distribution across a

considerable portion of Africa. For a relatively low cost and effort we were able to record the presence and distribution, together with other relevant information, of many established and invasive non-native plant species. This has provided a baseline that can be improved in future, providing policy makers and managers with critical information to guide future interventions. The incorporation of distribution maps in field guides (hard copies and e-books), together with images, descriptions and information on impacts and management have added considerable value to the distribution data. Prior to these surveys, there was almost no way in which farmers, land managers, government officials or researchers could access such information. There is now at least a starting point for the development of various management strategies and action plans, although keeping this up to date will remain challenging.

Development of these databases and field guides has led to requests to develop similar outputs for other data-poor countries. For example, one of us (ABRW) has now developed similar field guides to the invasive non-native plants of the Caribbean, Socotra (Yemen) and the Kingdom of Saudi Arabia. The benefit of field experience in the identification of species has largely made this possible. There is no doubt that the identification of non-native species in the landscape improves with experience. Other guides to the non-native and invasive animals of the Caribbean and Socotra have also been produced, although these are largely based on literature rather than roadside surveys. However, the process of developing these guides is generic, which facilitated their development.

Although there could be inherent shortcomings in roadside surveys (see Table 1), it is widely acknowledged that roads are one of the main invasion pathways in landscapes, facilitating the spread of invasive non-native plants (Lelong et al. 2007; Joly et al. 2011; Dar et al. 2015). Regular disturbances along roadsides allow for the establishment of non-native plants that then invade adjacent habitats (Foxcroft et al. 2011; Meunier & Lavoie 2012). Many emerging weeds have also been detected along roads (Kalwij et al. 2008; Christen & Matlack 2009; Mortensen et al. 2009; Pickering & Mount 2010), which means that roadside surveys can be very effective in early detection and rapid response programmes, an added benefit of these types of surveys.

Technological advances may also improve the efficacy of roadside surveys with the use of vehicle-mounted cameras. Using detection algorithms mounted on vehicles, Dyrmann et al. (2021) were able to record the presence of known invasive non-native plants growing along roadsides while travelling at speeds of over 100 km/h. As technology improves it may be possible to develop algorithms for all known invasive non-native plants in Africa, although such surveys will always be limited to areas immediately adjacent to roads, and inventories will need to be supplemented with other methods.

## Challenges to conducting roadside surveys

The efficacy of roadside surveys in recording invasive non-native plants has been questioned, because smaller plants, especially herbs, can easily be missed, and only the areas adjacent to roads can be surveyed (Henderson & Wilson 2017), although an experienced observer may be able to identify larger shrubs and trees some distance from the roadside. The ability to detect species further away from the road obviously also depends on the type of vegetation in which the survey is undertaken. It is limited in forests and woodlands, but easier in savanna and grasslands. Grasses are another group of species that are hard to identify during roadside surveys, other than some very conspicuous species, and climbers can also be missed, especially when they are not in flower.

In our surveys, shrubs and trees were the most frequently recorded plants (Table 3). This could demonstrate an inherent bias in roadside surveys because larger plants are easier to detect, or it could be an accurate reflection of the actual situation. It is well known that most poor people acquire utilitarian plants and are unlikely to acquire plants for ornamental purposes alone. Utilitarian plants may include species used for the demarcation of boundaries, medicinal purposes, shade and fuel. Surveys of nurseries in Nairobi, Kenya and elsewhere in Africa demonstrated a dearth of herbaceous ornamentals compared to the situation in South Africa. As such, we are confident that our surveys reflect the actual situation in the African countries covered here, although we acknowledge that roadside surveys could fail to detect less conspicuous non-native plant species, especially herbs.

Road infrastructure, or the lack thereof, also remains a challenge, especially in Africa. Sub-Saharan Africa has a road density of almost 2.3 km/100 km<sup>2</sup> compared to India, which averages 138 km/100 km<sup>2</sup> and the Association of Southeast Asian Nations countries where the average is 29.5 km/100 km<sup>2</sup> (AFC 2024). Across Africa 43% of roads are paved, of which 30% are in South Africa, which has the 12th largest road network in the world. Some data indicates that road density has actually declined in Africa over the past two decades. Road conditions can also hamper or even prevent some areas from being surveyed, especially during the rainy season, which is often considered to be the best time to undertake surveys.

Armed conflict or criminal activity can also inhibit or prevent surveys from being undertaken. For example, we were unable to undertake surveys in Burundi due to political instability, and eastern Ethiopia and Somalia was considered unsafe because of the continued presence of the militant political movement Al-Shabaab. Bandit activity also inhibited surveys in parts of northern Kenya.

Depending on road traffic, stopping on roadsides to confirm species presence can also be dangerous, an activity that has previously resulted in fatalities or serious injuries to colleagues. Stopping on roadsides can also expose those undertaking surveys to criminals. Access to land, especially private land adjacent to roadsides may also not always be possible. As such species presence in some areas cannot be confirmed.

Roadside surveys also require skills that are best acquired through experience. The more surveys that one undertakes, the better one becomes in identifying species, especially those growing some distance from the road. Familiarity with the species being recorded is also critical, or at least a very valuable asset. These problems would need to be overcome in part by purposefully nurturing ties with experts at universities and herbaria to increase skills. Of interest, a study on the identification of dinoflagellates found that accuracy was higher and more consistent in expert observers with field expertise than those with expertise gleaned from books (Culverhouse et al. 2003). Consistency of individuals with field expertise averaged 97% accuracy compared to only 75% among those whose expertise came from books (Culverhouse et al. 2003). Austen et al. (2016) were able to demonstrate that experts and non-experts both make many errors in the identification of bumblebee species when using standard field guide illustrations to identify species, demonstrating the value of field experience. As such, it is likely that using individuals with different levels of experience may lead to bias or errors. Should the same observers not be available for repeat surveys, that could also be seen as a serious challenge.

Individuals will also have biases in how they characterise non-natives as established or invasive. There is much confusion concerning the terms 'naturalised' (i.e., established) and 'invasive' and their associated concepts (Richardson et al. 2000). Plants are considered to be invasive if they produce 'reproductive offspring in areas distant from sites of introduction (approximate scales: >100 m over <50 years for taxa spreading by seeds and other propagules; >6 m / 3 years for taxa spreading by roots, rhizomes, stolons or creeping stems)' (Richardson et al. 2000). This type of detail is difficult to determine during roadside surveys, which means that the differentiation between established and invasive can often be blurred and subjective. Some surveyors are very conservative in their assessments, while others are more likely to characterise species as invasive when they may just be established.

Roadside surveys are often conducted as an adjunct to other work that involves travel to field sites or meetings. As such, they often have constraints on the amount of time that can be devoted to them. In remote or poorly developed areas, roadside surveys are also constrained by the need to consider accommodation along the way and to remain within budget and on schedule for other

purposes. It also often requires surveyors to be self-sufficient and flexible, so that routes can be changed if it becomes necessary to do so.

Despite these challenges, roadside surveys remain a cost-effective and efficient way to determine the presence and distribution of non-native plants, especially when road trips are undertaken in conjunction with other activities. Individuals involved in developing inventories are encouraged to always travel with a global positioning system to enable them to record the presence of non-native plants, especially those that may pose a threat to biodiversity and economic development.

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