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Citizen science reveals incipient naturalisation of non-native palms (Arecaceae) in South Africa

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ABSTRACT

Palms (Arecaceae) are among the most widely cultivated plant families globally, yet their invasion ecology remains poorly understood outside a few well-studied tropical systems. South Africa has cultivated non-native palms for over a hundred years, but no palm species are currently listed as invasive in national legislation. We used iNaturalist data, supplemented with herbarium and arboretum records, to compile the first comprehensive inventory of non-native palms in South Africa, model habitat suitability, identify areas of high naturalisation susceptibility, and propose monitoring priorities.

In total, 145 non-native palm taxa were recorded in the country. From 4,220 quality-filtered iNaturalist records, 3,873 represented planted individuals and 347 were wild-growing records indicative of naturalisation. Naturalisation probability, estimated using empirical Bayes shrinkage with Wilson score confidence intervals, was highest for *Livistona chinensis*, followed by *Caryota mitis* and *Phoenix dactylifera*. Seventeen taxa showed evidence of naturalisation, substantially exceeding the four currently recognised for South Africa in the Global Naturalized Alien Flora database.

An ensemble habitat suitability model evaluated using spatial block cross-validation (calibration TSS = 0.853, AUC = 0.972) identified the Human Footprint Index and

minimum winter temperature as the dominant predictors. A composite naturalisation susceptibility assessment integrating habitat suitability, propagule pressure, and proximity to existing naturalising populations identified 72 high-priority quarter-degree cells concentrated in three urbanised regions. These findings demonstrate the value of citizen science platforms for detecting incipient naturalisation events and a spatially explicit framework for prioritising early detection before invasive palm populations become widespread and costly to control.

Keywords: Arecaceae; citizen science; invasion debt; iNaturalist; monitoring; naturalisation; plant invasions

INTRODUCTION

Palms around the world

The family Arecaceae comprises about 2,600 species of climbers, shrubs, tree-like and stemless plants in 181 genera, all of which are commonly known as “palms” (Baker and Dransfield 2016; Fehr et al. 2020). Palms are among the best known and most extensively cultivated plant families globally (Dransfield et al. 2008); they have had deep cultural, economic and ecological importance to humans throughout history, particularly in the Middle East and North Africa, and many species yield foods, fibres, oils and other products of commercial value (Balick and Beck 1990). Their aesthetic qualities and functional versatility have made them among the most popular ornamental plants in tropical, subtropical and warm-temperate regions worldwide.

Many species are grown in urban landscapes, private gardens, botanical gardens and arboreta far outside their native ranges. This widespread and longstanding horticultural use has created the conditions for escape from cultivation, yet palms have historically been under-represented in inventories of naturalised and invasive species globally (Pyšek 1998). This pattern appears to be changing. A global review of invasive trees and shrubs listed 25 invasive palm species (Rejmánek and Richardson 2013), and a subsequent global synthesis documented 28 invasive and 86 naturalised palm species worldwide (Fehr et al. 2020). Although palms are generally perceived to be less invasive than other woody plants, Fehr et al. (2020) estimated that approximately 1.1% of all palm species have become invasive globally, exceeding the estimated 0.5–0.7% of woody plant species that are invasive worldwide (Richardson and Rejmánek 2011). Meyer et al. (2008) described ornamental palms on tropical islands as “time bombs in the garden” and identified 12 species that were already invasive or widely naturalised on tropical islands. More recent work has documented naturalisation events in Brazil (e.g. Mengardo and Pivello 2012; Taconi et al. 2021) and other regions, and naturalised palm populations are increasingly being recognised as capable of generating substantial ecological change in recipient ecosystems (Fehr et al. 2020). Overall, the available evidence points to a growing global footprint of naturalised and invasive palms, and several studies

suggest that major ecological impacts should be anticipated wherever self-sustaining populations become established (Conde et al. 2018; Numbere 2019; Fehr et al. 2020).

Several functional traits of palms help explain both their horticultural popularity and their propensity to naturalise outside their native ranges. Naturalised palm species are on average nearly twice as tall as non-naturalised species. This size advantage confers competitive ability, high fecundity and greater seed dispersal potential (Fehr et al. 2020). Palms originating from open habitats and dry forests show higher naturalisation rates than species from closed, moist forests. This pattern is associated with traits such as long-lived seeds and deep remote germination – a strategy, characteristic of many members of the subfamily Coryphoideae, in which a cotyledonary petiole buries the embryo below the soil surface before leaves emerge. These traits appear to pre-adapt palms to the disturbed, seasonally dry environments typical of urban and peri-urban landscapes globally. Critically, the traits favoured by the horticultural industry (e.g., fast growth, ease of propagation and tolerance of diverse environments) overlap substantially with the traits that promote naturalisation (van Kleunen et al. 2018, Fehr et al. 2020). This means that the most widely planted palm species are those most likely to escape cultivation and establish self-sustaining populations.

The Global Naturalised Alien Flora (GloNAF) database (version 3 available at: 10.5281/zenodo.17105725; van Kleunen et al. 2019; accessed 4 June 2026) currently lists 235 palm taxa recorded outside their native ranges across 141 regions worldwide, of which 163 are categorised as naturalised, 40 as both naturalised and invasive, and 32 as invasive only. However, GloNAF should not be regarded as a definitive or comprehensive inventory of naturalised palms globally. The database relies on published regional floras and checklists, which vary considerably in their coverage, currency, and taxonomic resolution, meaning that species with well-documented invasiveness in some regions could be absent from or incorrectly categorised. Palm species most commonly naturalised outside their native ranges include *Trachycarpus fortunei*, *Phoenix canariensis*, *Livistona chinensis*, *Washingtonia filifera var. robusta* (previously *W. robusta*) and *Archontophoenix cunninghamiana*, all of which are highly valued as ornamentals and are widely planted far beyond their native ranges (Fehr et al. 2020).

The ecological consequences of palm naturalisation can be substantial, adding urgency to early detection and monitoring. Fehr et al. (2020) documented 73 cases in which invasive palms affected other taxonomic groups or ecosystem functions, with competition against native flora and alteration of physical habitat structure being the most frequently reported effects. Dense stands of non-native palms can reduce light availability in the forest understorey, suppress native plant recruitment, and alter litter decomposition dynamics through the slow breakdown of their tough fronds (Fehr et al. 2024). Palm invasions can trigger trophic cascades: the colonisation of Pacific islands by *Cocos nucifera* reduced guano input from birds that avoided nesting in the non-native

trees, altering soil nutrient dynamics and plant community composition (Fehr et al. 2020). In the Brazilian Atlantic Forest, invasive palms reduce native seedling recruitment and threaten populations of native palm species (Conde et al. 2018). Despite growing documentation of these effects globally, the impacts of palm invasions remain understudied relative to those of other plant families, and much of the knowledge base rests on a small number of well-studied systems. Most palm species are exceptionally difficult and costly to remove once established. Unlike dicotyledonous trees, palms lack secondary woody growth and are instead composed of dense, fibrous vascular bundles that rapidly dull chainsaw blades and resist conventional mechanical removal methods. Their large size, extensive root systems, capacity for vegetative regrowth, and high rates of fecundity further complicate control efforts, which frequently require repeated interventions over many years with no guarantee of eradication (Fehr et al. 2020). No biological control agents are currently available for any naturalised palm species. These characteristics make established palm populations disproportionately costly to manage relative to other invasive woody plants, and strongly reinforce the case for pre-invasion risk assessment, early detection, and regulatory intervention before naturalised populations become more widespread.

Palms in South Africa

Although South Africa has a long history of introductions and invasions of non-native trees and shrubs (Richardson et al. 2003) – the country has been labelled the "World Capital of Tree Invasions" (Richardson et al. 2020) – no palms are currently listed in national legislation as invasive species (Wilson and Kumschick 2024). However, several palm species have already demonstrated weedy behaviour in South Africa, and many of the species most widely planted in the country are naturalised elsewhere in the world. These patterns suggest a substantial invasion debt (*sensu* Rouget et al. 2016) that warrants assessment.

South Africa has six native palm species, two of them endemic (*Jubaeopsis afra* Becc. and *Raphia australis* Oberm.) and four with parts of their range in the country: *Borassus aethiopum*, *Hyphaene coriacea*, *H. petersiana* and *Phoenix reclinata* (Siebert and Struwig 2019). All six have been cultivated both within and beyond their native ranges in South Africa. Non-native palm species have, however, been far more widely planted, and are conspicuous features of many South African landscapes, particularly in urban areas (Richardson and Potgieter 2024). Glen's (2002) book on "*Cultivated plants in South Africa*" lists 279 non-native palm species in 106 genera known to have been cultivated in the country, though many have only been grown in arboreta, botanical gardens and specialist collections. Lambert (1994) records 268 palm taxa planted in Durban Botanic Gardens alone, and Cheek et al. (2022) document 87 species across South African arboreta.

More recently, the community (citizen) science platform iNaturalist has accumulated over 5,900 records of planted individuals from 140 non-native palm species in South

Africa (https://www.inaturalist.org/projects/non-native-palms-planted-in-south-africa; accessed 18 July 2026), representing species from 43 of the genera listed by Glen (2002), as well as additional genera not previously recorded as cultivated in the country. Despite such substantial planting activity, a literature search in June 2026 revealed that only two non-native species have been formally reported as naturalised or invasive in South Africa: *Livistona chinensis* (Siebert et al. 2010) and *P. canariensis* (Henderson 2007). No palm species were included among the 86 taxa prioritised as emerging invaders for management in South Africa in 2004 (Nel et al. 2004), none have been identified as an eradication target by the South African National Biodiversity Institute or subjected to the formal risk analysis required for listing under the National Environmental Management: Biodiversity Act (Zengeya et al. 2026).

Rather than indicating a low invasion risk, this paucity of recorded palm invasions in South Africa could reflect a genuine lag in the naturalisation process. The long generation times of palms mean that decades can elapse between the first introduction of a species and the appearance of self-sustaining populations at significant distances from parent plants (Kowarik 1995; Fehr et al. 2020). Many of the species most widely planted in South Africa [including *P. canariensis*, *W. filifera var. robusta*, *L. chinensis* and *A. cunninghamiana* are already documented as naturalised or invasive elsewhere in the world (Henderson 2007; Siebert et al. 2010; Fehr et al. 2020), suggesting that propagule pressure in South Africa could already be sufficient to drive naturalisation in suitable habitats. The threat is likely to be amplified by ongoing climate change since palms are actively tracking rising temperatures by shifting their ranges to higher latitudes and elevations. For example, the expansion of *Trachycarpus fortunei* into temperate forests of the Southern European Alps (Walther et al. 2007) shows how warming winters combined with urban propagule sources can trigger naturalisation in regions where palms were previously unable to establish (Fehr et al. 2020; Jousson et al. 2022). Projected climatic warming is therefore likely to expand the area of suitable habitat for subtropical and warm-temperate palm species in South Africa, increasing opportunities for naturalisation.

South Africa's biodiverse and highly endemic flora, particularly in the Cape Floristic Region, one of the world's most species-rich hotspots, would be highly vulnerable to the impacts of palm invasions, making proactive monitoring an urgent conservation priority. However, management of invasive palms is likely to involve significant conflicts of interest, as non-native palms are deeply embedded in South Africa's urban and rural landscapes, where they are valued for their aesthetic appeal, contribution to property values, and association with tropical garden design. The removal of established palms from public spaces and private gardens will encounter opposition from property owners, municipalities, and the horticultural industry (Fehr et al. 2020). This tension between conservation objectives and the social value attached to ornamental palms reinforces the importance of early intervention through regulation of high-risk species, public

awareness, and the promotion of native alternatives before naturalised populations become entrenched and management options become both costly and contentious.

iNaturalist as a data source

The community science platform iNaturalist offers a cost-effective and spatially extensive tool for tracking the naturalisation trajectory of non-native palms in South Africa. iNaturalist aggregates georeferenced, photographic occurrence records submitted by members of the public and curated through a community identification process, generating data streams that can be updated continuously rather than at fixed survey intervals. The platform has been used to map planted tree distributions (Richardson and Potgieter 2024) and to compile inventories of naturalised plants in South Africa (Gildenhuys et al. 2024; Louw et al. 2024; Potgieter et al. 2024; Gildenhuys et al. 2025; Shepard et al. 2025). Palms are particularly well suited to photographic identification via iNaturalist: adult specimens can typically be identified to species level from images showing leaf form, trunk structure, crownshaft presence, armature and reproductive structures. The platform also provides a practical means of distinguishing planted individuals from self-seeding offspring (important for assessing naturalisation status) and of identifying the spatial clusters of cultivated parent populations most likely to act as sources for future spread. Seedlings, however, can usually only be identified to genus level, and iNaturalist data carry well-known limitations including spatial biases towards urban and accessible areas, uneven observer effort, and the risk of misidentification; but these can be addressed through systematic curation and targeted engagement with taxon experts and active iNaturalist observers.

This study aims to (1) compile a comprehensive inventory of non-native palm species recorded in South Africa by integrating community science, herbarium, botanical garden, and published records; (2) identify species that may constitute current or future invasion debt by estimating species-level naturalisation probabilities to rank species by their propensity for naturalisation relative to their planting abundance; (3) model habitat suitability to identify areas environmentally suitable for palm naturalisation across South Africa; and (4) develop a composite naturalisation susceptibility map to prioritise areas for monitoring and early detection.

METHODS

iNaturalist data collection

Two iNaturalist projects were created in November 2023 to collate distribution records of non-native palms in South Africa: (1) "Non-native palms planted in South Africa" (https://www.inaturalist.org/projects/non-native-palms-planted-in-south-africa) and (2) "Non-native palms naturalised in South Africa" (https://www.inaturalist.org/projects/non-native-palms-naturalized-in-south-africa). These projects served to communicate the extent of iNaturalist coverage achieved and

to identify regions and taxa requiring further surveying effort. Many active iNaturalist observers who regularly contribute records of trees in South Africa (see Richardson and Potgieter 2024) were contacted and requested to post records of both planted and wild-growing palms. In addition, observers who had already posted records of palms were contacted directly to verify identifications and the planted or wild-growing status of their observations.

iNaturalist separates observations into two quality grades: 'Research Grade' (RG) and 'Casual'. RG observations are the highest level of data quality and are integrated into other biodiversity databases (e.g. the Global Biodiversity Information Facility, GBIF). For an observation to be classified as RG, there must be photographic evidence of the organism, an identification at genus or species level, a GPS coordinate, and a date and observer record, together with a two-thirds consensus on the identification among the iNaturalist community (iNaturalist 2022). If any of these components are missing, the record is classified as Casual. An important additional criterion is whether the organism has been tagged as cultivated or wild; only observations tagged as wild can attain RG status. If there is any disagreement within the community over whether a plant is wild, the observation is immediately downgraded to Casual regardless of whether all other requirements are met. All data uploaded to the above projects up to and including 3 June 2026 were included in the analysis. Downloaded data were further filtered by excluding records with a positional accuracy exceeding 500 m or that lacked an image adequate for identification.

Data curation: distinguishing planted from wild-growing palms

Considerable effort was invested in curating the iNaturalist dataset to ensure that all records were correctly labelled as either cultivated (planted) or wild-growing (naturalising). Data editing followed the protocol described by Richardson and Potgieter (2024) and Potgieter et al. (2024). Each observation was thoroughly scrutinised using the supplied images and locality information to determine whether the location was unmistakably a garden, street, or other planted context, or whether it more likely represented a wild-growing individual. Google Street View (GSV) was frequently consulted to gain clearer contextual images than those provided in iNaturalist records, or to view the palm in its broader habitat setting. Where GSV imagery spanned multiple years, this was used to help determine whether a plant had been deliberately planted. In many cases, observers and/or regional botanical experts were contacted directly to confirm the planted or wild-growing status of records, and in some cases, localities were visited in the field by the authors. All species names were standardised against the World Checklist of Vascular Plants (Govaerts et al. 2021). RG observations were used as the primary proxy for naturalising palms, since iNaturalist records document the presence of wild-growing individuals at a single point in time and cannot verify the persistence of self-sustaining populations over multiple life cycles, a criterion required for a species to

be classified as naturalised *sensu* Richardson et al. (2000). Casual observations with confirmed cultivated status were used to map the distribution of planted individuals.

Species identifications and problematic taxa

Curation of iNaturalist records aimed to achieve a minimum of two agreeing identifications at species or genus level for each observation. Most adult non-native palms can be reliably identified to species from typical iNaturalist photographs, as images usually show leaf structure, trunk characteristics, crownshaft presence, armature (spines), and fruit or flower morphology. Where the initial identification was uncertain, local and international palm experts and relevant taxonomic treatments were consulted to verify records.

Some taxa, regardless of image quality, cannot be consistently identified to species level from iNaturalist observations. This can result from unclear distinctions between species within a genus, difficulty in distinguishing morphologically similar species, absence of sufficiently high-resolution images showing the diagnostic traits required for species-level identification, hybridisation between species, particular difficulty in identifying taxa at the juvenile stage, or a lack of available taxonomic expertise to resolve records to species level. Such taxa are designated "problematic taxa" in this study. Seedlings of species in the genera *Phoenix* and *Washingtonia* were especially difficult to identify to species level and, when in doubt, were retained at genus level only. A particular challenge was presented by *P. reclinata*, a species native to sub-Saharan Africa including South Africa, whose precise native range in the country was determined using the Red List of South African Plants (https://redlist.sanbi.org/species.php?species=3424-1). All records of this species were treated with particular care to ensure that wild-growing individuals within the documented native range were not misclassified as introduced naturalisations.

Initial errors in species identifications were examined by inspecting all records where more than one taxon name had been suggested by the observer or by subsequent members of the iNaturalist community. iNaturalist provides information on "other taxa commonly misidentified" for each species, which was accessed and recorded. The number of misidentifications per species was quantified using the count of species observations that received an alternative species-level identification suggestion other than the finally accepted consensus. The total number of disagreements was similarly calculated per species. These data provide an indication of the level of difficulty associated with correctly assigning the correct taxon name, time spent verifying identifications across taxa, and informs the confidence attributed to records in the dataset.

Spatial analysis

Filtered iNaturalist data were imported into R (version 4.3.1; R Core Team 2023) for spatial analysis using the packages *sf* (Pebesma 2018) and *ggplot2* (Wickham 2016). A

shapefile of level 2 quarter-degree grid cells (QDCs) covering South Africa was obtained from Zenodo (https://zenodo.org/doi/10.5281/zenodo.4457814). Occurrence records were spatially joined to the QDC grid, and species richness, and abundances, of planted and wild-growing non-native palms was mapped at the QDC level. For each QDC, the numbers of species with only Casual (planted) records, only RG (naturalising) records, and both record types were extracted. QDCs with at least one RG record were identified as sites of confirmed or probable naturalisation and used to assess the spatial extent of naturalisation across the country.

Non-native palm taxa inventory

A comprehensive inventory of non-native palm (Arecaceae) species recorded in South Africa was compiled by integrating occurrence data from four sources. iNaturalist observation records were downloaded and filtered to species-level records with a positional accuracy of ≤500 m and at least one identification agreement. Herbarium specimen records were obtained from the South African National Herbarium Computerised Information System (PRECIS; Glen 2002), and records were filtered to species-level identifications within the family Arecaceae. Records of palms cultivated in South African arboreta were obtained from Cheek et al. (2022), and species recorded as cultivated in South Africa were extracted from the catalogue of cultivated plants compiled by Glen (2002). All species names across the four sources were standardised to the World Checklist of Vascular Plants (WCVP; Govaerts et al. 2021) using the rWCVP package (Brown et al. 2023) in R, with fuzzy matching applied to resolve spelling variants and synonyms. For each species, the total number of records from iNaturalist, arboreta, and herbarium sources was compiled, along with the number of quarter-degree cells (QDCs) in which each species was recorded, and the naturalisation status as recorded in the GloNAF database (van Kleunen et al. 2019).

Habitat suitability modelling

To identify areas of high habitat suitability for naturalised palms across South Africa, an ensemble species distribution model (SDM) was constructed using the biomod2 package (Thuiller et al. 2009) in R. RG records were spatially thinned to a minimum distance of 1 km to reduce spatial autocorrelation and the effects of uneven sampling effort, which can otherwise cause models to track survey intensity rather than habitat suitability (Boria et al. 2014; Fourcade et al. 2014). Nine candidate environmental predictors were initially considered: six bioclimatic variables from WorldClim v2.1 at 30 arc-second resolution (BIO1, BIO6, BIO8, BIO13, BIO14, BIO15; Fick amd Hijmans 2017), elevation (SRTM 30 arc-second; Farr et al. 2007), the Human Footprint Index (HFI; Venter et al. 2016), and distance to the nearest river. Distance to rivers was calculated as the Euclidean distance from each raster cell to the nearest feature in the Department of Water and Sanitation (DWS) national rivers dataset, which includes all perennial, non-perennial, and unclassified watercourses across South Africa (Strahler orders 1 to 7). Following variance inflation factor analysis (VIF < 5), three collinear variables were

removed (BIO1, BIO15, and elevation), leaving six predictors in the final model: minimum temperature of the coldest month (BIO6), mean temperature of the wettest quarter (BIO8), precipitation of the wettest month (BIO13), precipitation of the driest month (BIO14), HFI, and distance to rivers.

Five algorithms were fitted: generalised linear models (GLM), generalised boosted models (GBM), generalised additive models (GAM), random forest (RF), and MaxEnt (via the maxnet package; Phillips et al. 2017). Three pseudo-absence datasets of 10,000 randomly selected background points each were generated. Model transferability was assessed using spatial block cross-validation (Roberts et al. 2017) to provide unbiased estimates of predictive performance for spatially clustered citizen science data. Model performance was assessed using the True Skill Statistic (TSS) and the area under the receiver operating characteristic curve (AUC). GAM and RF were excluded from the ensemble due to poor spatial transferability (mean validation TSS = 0.484 and 0.279, respectively, below the 0.5 retention threshold). The final weighted mean ensemble comprised three algorithms (GLM, GBM, MaxEnt), with individual model contributions weighted by TSS. Variable importance was estimated using three-fold permutation. Habitat suitability was converted to a binary suitable/unsuitable classification using the TSS-optimised threshold, which was also applied as the suitability criterion in the naturalisation risk assessment.

Naturalisation probability

Taxa

To quantify the propensity of each non-native palm species to naturalise in South Africa, the proportion of RG records relative to total iNaturalist records was calculated for each species as an estimate of naturalisation probability. Total record abundance was reported alongside this proportion as a separate axis reflecting planting effort and detectability. Presenting these two dimensions independently allows species that are frequently naturalising but rarely planted (high probability, low abundance) to be distinguished from species that are widely planted with occasional naturalisation (low probability, high abundance), each of which may warrant different management responses.

To account for variation in sample size across species, naturalisation probability estimates were adjusted using empirical Bayes shrinkage (Beta-binomial method of moments), which draws species with few records towards the overall mean naturalisation rate across all species with RG records, reducing the influence of extreme proportions arising from small sample sizes. The parameters of the Beta prior distribution were estimated from the observed distribution of naturalisation rates using the method of moments. Empirical Bayes estimates were reported only for the 17 species with at least one RG record; for species with zero RG records, the shrinkage estimate is dominated by the prior rather than the data and does not reflect species-

specific naturalisation tendency, so these species were assigned a naturalisation probability of zero in the species table. Wilson score 95% confidence intervals were calculated for the RG proportion of each species, as the Wilson interval provides more accurate coverage than the Wald interval for small samples and for proportions near zero or one (Wilson 1927; Brown et al. 2001), both of which are common in this dataset. For species with zero RG records, the Wilson confidence interval upper bound provides the most informative quantity, indicating the maximum naturalisation probability that cannot be excluded given the available sample size. Species were ranked by the lower bound of the Wilson 95% confidence interval rather than the point estimate, as this ranking prioritises species for which there is confident evidence of elevated naturalisation probability over those with high but uncertain estimates driven by small sample sizes. Species were visualised in a forest plot showing the empirical Bayes point estimate and 95% Wilson confidence interval, with point size scaled by total record abundance and colour coded by sample size tier (well sampled, $n \geq 50$; moderately sampled, $10 \leq n < 50$; poorly sampled, $n < 10$).

Area

To identify priority areas for palm naturalisation monitoring and management, a composite naturalisation susceptibility assessment was conducted at the quarter-degree cell (QDC) level across South Africa, using level 3 QDCs (approximately 13 × 14 km) as the finer spatial resolution provides a more operationally relevant scale for directing field-based surveillance and management interventions.

Three spatially explicit criteria were evaluated for each QDC. First, habitat suitability was derived from the ensemble species distribution model; QDCs with a mean predicted suitability exceeding the TSS-optimised threshold (0.308) were classified as environmentally suitable for palm naturalisation. Second, propagule pressure was quantified as the number of quality-filtered Casual (planted) iNaturalist records per QDC; QDCs with ≥ 5 Casual records were considered to have sufficient ornamental planting activity to serve as a source of propagules for naturalisation. Third, proximity to the invasion front was calculated as the Euclidean distance from each QDC centroid to the nearest quality-filtered RG (naturalising) iNaturalist record, projected to UTM zone 35S for accurate distance measurement; QDCs within 25 km of an existing naturalising population were considered at elevated susceptibility to colonisation via natural dispersal (Thomas and Moloney 2015).

Each QDC was scored according to the number of criteria met simultaneously. QDCs meeting all three criteria were classified as Very High susceptibility, those meeting two as High, and those meeting one as Moderate or Low depending on whether the composite score exceeded the median for one-criterion QDCs. The composite score was calculated as a weighted sum of three normalised components: habitat suitability (weight = 0.40), propagule pressure (0.35), and proximity to the invasion front (0.25). QDCs meeting no criteria were unclassified. It should be noted that the three criteria are

not fully independent: habitat suitability is partly driven by the Human Footprint Index, which correlates spatially with both iNaturalist observer effort and ornamental planting density. The assessment should therefore be interpreted as identifying areas where multiple indicators of naturalisation susceptibility converge, rather than as a formal probabilistic model.

RESULTS

Non-native palm species inventory

In total, 145 non-native palm taxa were recorded in South Africa across iNaturalist, arboretum (Cheek et al. 2022), and herbarium (Glen 2002) sources. Of these, 115 taxa were represented by iNaturalist records (Table 1), with supplementary records from arboreta and herbaria. The most frequently recorded species were *Phoenix canariensis* (1,203 records), *Washingtonia filifera* var. *robusta* (1,006), and *Syagrus romanzoffiana* (584). Four palm taxa are currently categorised for South Africa in the GloNAF database: *L. chinensis* (naturalised), *P. canariensis* (invasive), *P. dactylifera* (invasive), and *W. filifera* var. *robusta* (invasive). However, 17 taxa had Research Grade records indicative of naturalisation, substantially exceeding the four taxa captured in GloNAF.

Species richness of non-native palms

A total of 4,220 species-level iNaturalist records met the quality criteria and fell within the South African mainland boundary; these comprise 3,873 Casual (planted) and 347 RG (wild-growing) records (Online Resource 1). Non-native palm species richness was concentrated along the coastal margins of the country, with notable hotspots in the greater Durban area (KwaZulu-Natal), Cape Town and Stellenbosch, while the arid interior supported few or no records (Fig. 1). Planted palm species richness was highest in the Durban area, where a single QDC contained 38 planted species, the greatest planted richness recorded nationally (Fig. 1a). Naturalising palm species richness was considerably lower, with a maximum of five naturalising species recorded in any single QDC (Fig. 1b). The QDC with the highest naturalising palm species richness is on the east coast near the city of Durban (18 planted species, 5 naturalising species, 38 RG records). Of the 264 QDCs containing palm records, 56 contained both planted and naturalising records, 193 contained only planted records, and 15 contained only naturalising records (Fig. 2). QDCs with at least one RG record, considered sites of confirmed or probable naturalisation, numbered 71.

Abundance of non-native palm records

Patterns of record abundance mirrored those of species richness, with the highest densities of both planted and naturalising records occurring in coastal urban centres (Fig. 2). Planted record abundance was greatest in the Cape Town and Durban metropolitan areas (Fig. 2a), reflecting the widespread use of palms in urban horticulture. Naturalising record abundance was similarly concentrated along the

KwaZulu-Natal coast, and Cape Town and Stellenbosch (Fig. 2b), although at substantially lower densities than planted records. The highest naturalising species richness occurred in a QDC near Durban, KwaZulu-Natal, with 38 RG records of five species (Fig. 3a). The highest abundance of naturalising palm records was concentrated in a single QDC in Stellenbosch, with 98 RG records representing two species (Fig. 3b). The Stellenbosch hotspot was dominated by high-density naturalisation of two species, whereas the Durban hotspot was characterised by lower record abundance but greater species diversity.

The distribution of records across QDCs was highly skewed, with a small number of cells accounting for a disproportionately large share of records, necessitating log-transformation of the abundance scales for visualisation.

Habitat suitability modelling

After spatial thinning to a minimum distance of 1 km, 244 RG records were retained for modelling. Following variance inflation factor analysis (VIF < 5), six predictors were retained in the final model: HFI, minimum temperature of the coldest month (BIO6), mean temperature of the wettest quarter (BIO8), precipitation of the wettest month (BIO13), precipitation of the driest month (BIO14), and distance to rivers. Five algorithms were fitted (GLM, GBM, GAM, RF, MaxEnt) and evaluated using spatial block cross-validation. GAM and RF were excluded from the ensemble due to poor spatial transferability (mean validation TSS = 0.484 and 0.279, respectively, below the 0.5 retention threshold). The final weighted mean ensemble, comprising GLM (mean validation TSS = 0.662), GBM (0.649), and MaxEnt (0.614), achieved a calibration TSS of 0.853 and AUC of 0.972, with a sensitivity of 93.8% and specificity of 91.6% (Online Resource 2).

Variable importance analysis revealed that the HFI was the most influential predictor of palm naturalisation habitat suitability (mean permutation importance = 0.515), followed by minimum temperature of the coldest month (0.234) (Fig. 4). Together these two variables accounted for approximately 75% of total variable importance. The remaining variables contributed moderately: precipitation of the wettest month (0.050), precipitation of the driest month (0.031), mean temperature of the wettest quarter (0.031), and distance to rivers (0.028). The dominance of HFI is consistent with the interpretation that proximity to human-modified landscapes, where palms are planted as ornamentals, is the primary driver of naturalisation opportunities, although this signal may partly reflect the spatial correlation between iNaturalist observer effort and urbanised areas.

The ensemble habitat suitability map identified the highest suitability along the KwaZulu-Natal and Eastern Cape coastline, the greater Durban and Richards Bay metropolitan areas, and the coastal lowlands extending to the Wild Coast (Fig. 4). Secondary areas of moderate suitability were predicted around Stellenbosch and the greater Cape Town

metropolitan area, the Garden Route, and the Lowveld region of Mpumalanga and Limpopo provinces. The interior Highveld, the arid western regions, and the Karoo were predicted as largely unsuitable, consistent with the low minimum winter temperatures and low precipitation that characterise these areas. The binary suitability map, derived using the TSS-optimised threshold of 0.308, estimated approximately 119,958 km^2 (9.8% of South Africa's land area) as suitable habitat for palm naturalisation.

The spatial distribution of predicted suitable habitat closely mirrors the current distribution of RG records (Fig. 4) but extends into several areas where naturalising palms have not yet been recorded, particularly along the northern KwaZulu-Natal coast and parts of the Eastern Cape. These areas may represent regions of unfulfilled invasion potential, where environmental conditions are suitable for palm naturalisation but where propagule pressure from ornamental plantings has been insufficient or naturalisation has not yet been detected.

Naturalisation susceptibility

Taxa

Of the 145 non-native palm taxa recorded in South Africa, 17 had at least one RG iNaturalist record. Species were ranked by the lower bound of the Wilson 95% confidence interval to prioritise those for which there is confident evidence of elevated naturalisation probability (Table 1; Fig. 5).

Livistona chinensis ranked first (empirical Bayes estimate = 0.357, lower CI bound = 0.29; 64 RG out of 177 total records), indicating that over a third of all iNaturalist records for this species in South Africa represent wild-growing individuals. *Washingtonia filifera* var. *robusta* ranked third by lower CI bound (0.09; estimate = 0.112, 113 RG out of 1,006), followed by *Caryota mitis* (0.08; estimate = 0.17, 5 RG out of 29) and *Phoenix dactylifera* (0.08; estimate = 0.15, 9 RG out of 60).

Several species with few total records had elevated point estimates but correspondingly wide confidence intervals, reflecting the uncertainty inherent in small samples. *Aiphanes horrida* (estimate = 0.37, CI: 0.21–0.94; 2 RG out of 3) ranked second by lower CI bound but this was based on only three records. These species warrant targeted field surveys to determine whether the high RG proportions reflect genuine naturalisation or isolated occurrences.

Washingtonia filifera var. *robusta* and *P. canariensis*, the two most abundantly recorded non-native palms in South Africa (1,006 and 1,203 total records, respectively), had comparatively low naturalisation probabilities (0.112, 95% CI: 0.09–0.13 and 0.078, 95% CI: 0.06–0.09, respectively) but narrow confidence intervals and the highest absolute numbers of RG records (113 and 93). This distinction highlights the value of reporting naturalisation probability alongside total abundance: these species would not be identified as high priority based on naturalisation probability alone, yet their large

absolute numbers of naturalising individuals and wide geographic spread suggest that their naturalisation is more established than their probability estimates imply. Conversely, *L. chinensis* had both the highest naturalisation probability and a narrow confidence interval, confirming it as the species of greatest concern.

Area

Of the 7,575 level 3 QDCs covering mainland South Africa, 928 (12.2%) met at least one naturalisation susceptibility criterion, while 6,647 (87.8%) met none. A total of 72 QDCs (1.0%) were classified as Very High susceptibility, meeting all three criteria simultaneously (habitat suitability ≥ 0.308, ≥ 5 Casual records, and within 25 km of an existing naturalising population). A further 209 QDCs (2.8%) were classified as High (two criteria met), 324 (4.3%) as Moderate, and 323 (4.3%) as Low (Fig. 5).

The 72 Very High QDCs were distributed across four primary regions: the KwaZulu-Natal coast from Durban to the Zululand coast (n = 24), the Cape Town metropolitan area and Cape Peninsula (n = 22), the Gauteng and Limpopo provinces (n = 16), and the Garden Route and Eastern Cape coast (n = 7), with individual QDCs on the West Coast, in the North West province, and the KwaZulu-Natal interior. The highest-scoring QDC (composite score = 0.94) was located in the Cape Town southern suburbs, with 334 Casual records representing 28 planted species, a mean habitat suitability of 0.85, and 85 existing RG records of two naturalising species (Fig. 5). Along the KwaZulu-Natal coast, the highest-scoring QDC (composite score = 0.71) was located near eThekwini (Durban), with 104 Casual records of 38 species and a mean habitat suitability of 0.89. Despite ranking sixth overall, this QDC had the highest planted species richness of any Very High QDC nationally, suggesting that species diversity in cultivation may be a driver of naturalisation opportunity. In contrast, the Durban QDC ranking eleventh (E030S29DDB) had fewer planted records (30 Casual, 10 species) but the highest naturalising species richness of any QDC in South Africa (28 RG records, 5 naturalising species). Two Very High QDCs had no current RG records despite meeting all three criteria, representing potential invasion debt sites where targeted early detection surveys are most warranted.

High susceptibility QDCs extended beyond the metropolitan centres along the KwaZulu-Natal south coast, the Garden Route between Mossel Bay and Gqeberha, and parts of the Mpumalanga and Limpopo Lowveld (Fig. 5). Moderate QDCs were more widely distributed, occurring in secondary urban centres including Mbombela, Polokwane, and Gqeberha. Low QDCs were predominantly located in peri-urban areas and smaller towns where only one criterion, typically habitat suitability or low-level propagule pressure, was met. The arid western interior, the Karoo, and the cold interior Highveld were largely unclassified, consistent with the low habitat suitability predicted by the ensemble SDM for these regions.

DISCUSSION

Our inventory of 145 non-native palm taxa transforms the perception of palms as an invasion threat in South Africa. Before this study, only two non-native palms (*L. chinensis* (Siebert et al. 2010) and *P. canariensis* (Henderson 2007)) had been formally reported as naturalised or invasive in the country, and none had been flagged for management or regulatory attention (Nel et al. 2004; Zengeya et al. 2026). Yet our analysis of curated iNaturalist records, integrated with herbarium and arboretum data, reveals that at least 71 level 2 QDCs contain wild-growing palms, and that naturalisation signals are detectable for 17 species. The discrepancy between the two species previously documented, and the far larger pool now shown to be naturalising, mirrors findings for other woody genera assessed using community-science data in South Africa, including *Ligustrum* (Shepard et al. 2025), *Melaleuca* (Potgieter et al. 2024), *Myoporum* (Louw et al. 2024) and *Quercus* (Gildenhuys et al. 2024). In each case, the systematic interrogation of iNaturalist records uncovered naturalisation that conventional herbarium- or field-based surveys had missed. Palms, with their conspicuous growth forms and photogenic diagnostic features, are especially well suited to this approach and our results add weight to the argument that community science platforms are reshaping the detection of early-stage woody plant invasions.

Current naturalisation and invasion status

The naturalisation probability analysis identified *L. chinensis* as the taxon showing the strongest naturalisation signal (empirical Bayes estimate = 0.357, 95% CI: 0.29–0.43), followed by *C. mitis* (0.17, 95% CI: 0.08–0.35) and *P. dactylifera* (0.15, 95% CI: 0.08–0.26). This is consistent with independent lines of evidence: *L. chinensis* is the longest-recognised naturalised palm in the country (Siebert et al. 2010), is the only taxon listed as naturalised for South Africa in GloNAF, and has the highest proportion of wild-growing records of any well-sampled taxon (64 of 177 records). The prominence of *W. filifera* var. *robusta* is notable as one of only three non-native palm taxa listed as invasive in South Africa in GloNAF (alongside *P. canariensis* and *P. dactylifera*). Our data corroborate this listing with 113 RG records, more than for any other taxon, and the widest overall recorded distribution of any non-native palm in the country. Although its naturalisation probability was comparatively low (0.112, 95% CI: 0.09–0.13), the narrow confidence interval and the large absolute number of naturalising individuals indicate that its naturalisation is well established. *Phoenix canariensis* and *S. romanzoffiana* showed a similar pattern: low naturalisation probabilities (0.078, 95% CI: 0.06–0.09 and 0.061, 95% CI: 0.04–0.08, respectively) but narrow confidence intervals and large absolute numbers of RG records (93 and 35), reflecting the large planted component of their records rather than an absence of wild recruitment. *Phoenix dactylifera* presents the converse case: it had the third-highest naturalisation probability (0.15, 95% CI: 0.08–0.26) on only nine RG records, and is listed as invasive in GloNAF, yet its small number of wild-growing records suggests that naturalisation remains at an early stage.

A second tier of taxa has fewer wild-growing records, placing them at the casual-to-naturalised transition. Seven additional taxa had RG records with lower naturalisation probabilities: *Archontophoenix cunninghamiana* (7 RG of 84 records; naturalisation probability 0.086), *Cocos nucifera* (5 of 74; 0.072), *Trachycarpus fortunei* (3 of 53; 0.063), *W. filifera* (3 of 62; 0.055), *Roystonea regia* (3 of 71; 0.048), *Chrysalidocarpus lutescens* (1 of 131; 0.012) and *Caryota urens* (1 of 11; 0.107). These taxa represent those most likely to progress further along the introduction-naturalisation-invasion continuum in the coming decades, and they warrant particular attention in any monitoring programme. Notably, the empirical Bayes approach reveals that *C. urens*, despite having only one RG record, has a shrunken naturalisation probability (0.107) comparable to that of *W. filifera* var. *robusta* (0.112), suggesting that its naturalisation potential may be underappreciated relative to more conspicuously planted species.

Habitat suitability

The ensemble habitat suitability model evaluated using spatial block cross-validation and comprising three algorithms (GLM, GBM, MaxEnt) after excluding GAM and RF for poor spatial transferability, achieved a calibration TSS of 0.853 and AUC of 0.972. The HFI was the most important predictor (mean permutation importance = 0.515), consistent with global patterns documented by Fehr et al. (2020), who found a positive relationship between HFI and the proportion of naturalising palms in a region (Nagelkerke's $R^2 = 0.25$) and that every region with native palms and HFI > 20 had at least one naturalising palm species. This underscores the mechanistic link between human-modified landscapes and palm invasions: urbanised areas harbour high densities of ornamental plantings, creating sustained propagule pressure that facilitates escape and establishment (van Kleunen et al. 2018; Fehr et al. 2020). The primacy of HFI over purely climatic variables aligns with Williams et al. (2024), who found that human modification was the top-performing predictor across 220 invasive terrestrial plant species, outperforming traditional bioclimatic variables. However, the dominance of HFI should be interpreted with caution, as iNaturalist records are spatially biased towards urban areas and accessible locations (Dimson et al. 2023), and the random background points used in this study do not control for this observer effort bias.

Minimum temperature of the coldest month (BIO6) was the second most important predictor (0.234), together with HFI accounting for approximately 75% of total variable importance. This reflects the frost sensitivity of palms as a predominantly tropical and subtropical family, and the few naturalising records from the cold interior Highveld and strongly seasonal grasslands supports the interpretation that winter cold represents a hard physiological barrier to palm establishment (Qian et al. 2022; Williams et al. 2024). The remaining predictors contributed moderately: precipitation of the wettest month (0.050), precipitation of the driest month (0.031), mean temperature of the wettest quarter (0.031), and distance to rivers (0.028). The relatively low importance of distance to rivers likely reflects partial redundancy with HFI, which already captures gradients in

urbanisation and landscape modification that correlate with proximity to riparian corridors. Nevertheless, the inclusion of distance to rivers as a predictor is ecologically justified, as riparian corridors can facilitate naturalisation through moisture provision, mesic microclimates, and potential hydrochorous dispersal.

The spatial distribution of predicted suitable habitat (concentrated along the KwaZulu-Natal and Eastern Cape coastline, Cape Town and Stellenbosch in the Western Cape, and the Mpumalanga Lowveld) closely mirrors both the current distribution of naturalising records and the global pattern described by Fehr et al. (2020). However, the model also identified areas of high suitability where naturalising palms have not yet been recorded, particularly along the northern KwaZulu-Natal coast and parts of the Wild Coast of the Eastern Cape. These areas may represent unfulfilled invasion potential, locations where conditions are conducive to naturalisation but where propagule pressure has been insufficient or naturalisation has not yet been detected. Given the long generation times of palms and the well-documented lag phases between introduction and spread (Kowarik, 1995; Fehr et al. 2020), the current distribution of naturalising palms in South Africa likely underestimates the eventual extent of palm invasions under prevailing climatic and land-use conditions.

Invasion debt and spatial patterns

The central interpretation arising from our data is that South Africa carries a substantial and largely unrecognised invasion debt (*sensu* Rouget et al. 2016) with respect to non-native palms. The signal is clearest in the mismatch between cultivation intensity and naturalisation. The most widely planted taxa, *P. canariensis* (1,203 records), *W. filifera* var. *robusta* (1,006), and *S. romanzoffiana* (584), are planted extensively across the country's urban landscapes, yet the proportion of records representing wild-growing individuals remains modest for all but a handful of taxa. While this low naturalisation fraction could be interpreted to imply that non-native palms currently pose little threat, the long generation times characteristic of palms mean that decades typically elapse between widespread planting and the appearance of self-sustaining populations at significant distances from parent plants (Kowarik 1995; Fehr et al. 2020). The current configuration (extensive, decades-old plantings of species known to be invasive elsewhere, coupled with only incipient naturalisation) is the signature of a lag phase preceding wider spread. Many of the species most widely planted in South Africa, including *P. canariensis*, *W. filifera* var. *robusta*, *L. chinensis*, and *A. cunninghamiana*, are already naturalised or invasive in climatically comparable regions worldwide (Fehr et al. 2020), indicating that propagule pressure within South Africa is likely already sufficient to drive naturalisation wherever recipient habitats are suitable.

Spatial patterns reinforce this interpretation. Both planted and naturalising palm records were strongly concentrated along the coastal margins of the country, with the greatest richness and abundance occurring in the subtropical greater Durban area (KwaZulu-Natal) and the Mediterranean-climate Western Cape around Cape Town and

Stellenbosch. This distribution reflects the interaction between climatic suitability and propagule pressure: palms are planted most intensively in warm, frost-free, high-rainfall coastal cities, and these same conditions favour establishment. The single level 2 QDC in Durban supported 38 cultivated species (the highest planted richness recorded nationally), while the coastal belt of KwaZulu-Natal also contained the highest concentrations of wild-growing records, including the QDC with the greatest naturalising species richness in the country (5 species, 28 RG records). By contrast, the arid interior supported few or no palm records, consistent with climatic limitation. The naturalisation susceptibility assessment identified two very high-priority QDCs with no current RG records despite meeting all three criteria, representing sites where invasion debt may be actively accumulating and where targeted early detection surveys could intercept naturalisations before populations become established.

This invasion debt is likely to be realised more rapidly under ongoing climate change. Palms are actively tracking rising temperatures by expanding to higher latitudes and elevations (Walther et al. 2007), and the documented spread of *Trachycarpus fortunei* into temperate forests of the Southern European Alps demonstrates how warming winters, combined with abundant urban propagule sources, can trigger naturalisation in regions that were previously climatically unsuitable (Jousson et al. 2022).

Although these spatial patterns should be interpreted with some caution because iNaturalist observations are subject to well-known urban and accessibility biases (cf. Potgieter et al. 2024; Dimson et al. 2023), the concentration of naturalising palms within climatically favourable coastal cities is ecologically consistent and unlikely to be an artefact of sampling alone. The habitat suitability model's reliance on the Human Footprint Index as its dominant predictor (accounting for approximately 50% of variable importance) may partly reflect this observer effort bias rather than a purely ecological signal, and future analyses incorporating a target-group background (Phillips et al. 2009) would help to disentangle these effects.

Monitoring, early detection and naturalisation susceptibility

The results of this study provide two complementary tools for guiding monitoring and early detection efforts for non-native palm invasions in South Africa: the naturalisation susceptibility map, which guides spatial prioritisation, and the naturalisation probability metric, which guides species-level prioritisation. Used together, these tools address the two fundamental questions facing invasive species managers: where should we look, and what should we look for (Jarnevich et al. 2023).

The composite naturalisation susceptibility map provides a spatially explicit, multi-criteria framework for prioritising palm invasion monitoring and management across South Africa. The concentration of very high-priority QDCs along the KwaZulu-Natal coast from Durban to the Zululand coast (n = 24), in the Cape Town metropolitan area and Cape Peninsula (n = 22), and in the Gauteng and Limpopo provinces (n = 16) reflects

the convergence of the key drivers of palm naturalisation identified throughout this study. The criteria-based approach adopted here identifies a set of 72 very high-priority QDCs (1.0% of all QDCs) where monitoring and early intervention are most warranted. It should be acknowledged that the three criteria used in the assessment (habitat suitability, propagule pressure, and proximity to naturalising populations) are not fully independent, as all are partly influenced by the spatial distribution of urbanisation and iNaturalist observer effort. The assessment should therefore be interpreted as identifying areas where multiple indicators of naturalisation susceptibility converge, rather than as a formal probabilistic model. Nevertheless, these QDCs represent the most cost-effective targets for field-based surveillance, as they are the locations where new naturalisation events are most likely to occur.

This approach is conceptually aligned with the invasion debt framework (Rouget et al. 2016), which recognises that species may be present in a region for extended periods before naturalisation occurs, particularly where environmental conditions are suitable but stochastic processes such as dispersal limitation or insufficient propagule pressure delay establishment. The identification of very high-priority QDCs with no current RG records, as well as high-priority and moderate-priority QDCs with high habitat suitability and propagule pressure, could represent sites where invasion debt is accumulating. These areas are of particular management concern because the conditions for naturalisation are already present, yet establishment has either not occurred or has not yet been detected. Targeted surveys in these QDCs could detect incipient naturalisations while eradication remains feasible (Reaser et al. 2020; Taconi et al. 2021).

At the species level, the naturalisation probability analysis provides an empirical basis for constructing a watch list of priority species for monitoring. Species with high empirical Bayes naturalisation probabilities and narrow confidence intervals, particularly *L. chinensis* (0.357, 95% CI: 0.29–0.43), *C. mitis* (0.17, 95% CI: 0.08–0.35), and *P. dactylifera* (0.15, 95% CI: 0.08–0.26), should be the primary targets for field verification within very high and high risk QDCs, as these species have demonstrated the greatest propensity for naturalisation in South Africa relative to their planting abundance. Species with lower naturalisation probabilities but large absolute numbers of RG records, such as *W. filifera* var. *robusta* (0.112, 95% CI: 0.09–0.13; 113 RG records) and *P. canariensis* (0.078, 95% CI: 0.06–0.09; 93 RG records), should also be prioritised given that their naturalisation is already widespread. Additionally, taxa currently recorded only as Casual (planted) in South Africa but listed as naturalised in other regions through GloNAF should be included on regional watch lists as "doorstep species" (*sensu* Jarnevich et al. 2023): species with a documented global capacity for naturalisation that are already present in cultivation and could establish wild populations given sufficient time and opportunity. Our analysis identified 17 species with RG records indicative of naturalisation, yet only four palm taxa are currently categorised

for South Africa in GloNAF (*L. chinensis*, *P. canariensis*, *P. dactylifera*, and *W. filifera* var. *robusta*), underscoring the extent to which palm naturalisation in South Africa is underrepresented in global databases.

The absence of any non-native palm from South Africa's national invasive species regulations (Zengeya et al. 2026) is increasingly difficult to justify considering our findings. We recommend that the species with the highest naturalisation probabilities and largest numbers of wild-growing records (*L. chinensis*, *W. filifera* var. *robusta*, and *P. canariensis*) be prioritised for formal risk analysis as a prerequisite for possible listing under the National Environmental Management: Biodiversity Act 10 of 2004. Palms are large, deep-rooted, and highly fecund, making them difficult and expensive to remove once established, frequently requiring repeated interventions with no guarantee of eradication (Fehr et al. 2020). The invasion debt framework highlights a narrowing window of opportunity during which intervention remains cost-effective and eradication remains feasible while populations are still localised, as has been demonstrated for incipient palm invasions elsewhere (Taconi et al. 2021).

Limitations and future directions

Beyond the spatial and observer-effort, seedlings of several genera (notably *Phoenix* and *Washingtonia*) frequently could not be resolved below genus level, meaning that the earliest and most informative stage of naturalisation is under-detected for some of the highest-risk taxa. A subset of "problematic taxa" could not be reliably identified to species even as adults, owing to morphological similarity, hybridisation or insufficient image quality (Online Resource 1). RG status, while a useful and defensible proxy for naturalisation, is not a perfect one, and the considerable curation effort required to convert raw records into a reliable dataset should not be underestimated. As with the *Melaleuca* assessment of Potgieter et al. (2024), the reliability of our conclusions rests heavily on this manual verification, including direct engagement with regional experts and observers.

A methodological consideration specific to *Cocos nucifera* concerns the presence of iNaturalist records of coconuts washed up on beaches along the KwaZulu-Natal and Eastern Cape coastlines. These records likely document the natural hydrochorous dispersal of coconut fruits via ocean currents rather than the presence of established or naturalising individuals, and where identified, such observations were annotated as having ‘no evidence of a living organism’ on iNaturalist and excluded from the analysis. However, it is likely that some of these records remain in the dataset and might inflate its naturalising distribution. The RG records of *C. nucifera* in our dataset might reflect the long-distance oceanic dispersal (the primary natural dispersal mechanism by which *C. nucifera* has colonised tropical coastlines globally; Harries 1978) or escapes from cultivation in coastal gardens and amenity plantings in the region rather than natural dispersal events.

The Wilson score confidence intervals provide a transparent, sample-size-aware estimate of naturalisation probability, but should be interpreted as descriptive summaries rather than formal statistical inferences.

The use of iNaturalist Casual (planted) records as a proxy for propagule pressure is subject to observer bias, with recording effort concentrated in accessible urban areas and along major transport routes (Dimson et al. 2023). QDCs in rural or remote areas may support substantial ornamental palm plantings that are not captured by community science observations, potentially underestimating naturalisation risk in these regions.

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Competing interests

The authors have no relevant financial or non-financial interests to disclose.

Author contributions

LJP and DMR conceived the study, curated the data, and administered the project, and wrote the original draft. LJP designed the methodology, performed the formal analyses, validated the results, and produced the visualisations. DMR contributed to the methodology and investigation, and secured funding. Both authors reviewed and edited the manuscript and approved the final version.

Data availability statement

All iNaturalist data used in this study are publicly accessible through two dedicated iNaturalist projects: "Non-native palms planted in South Africa" (https://www.inaturalist.org/projects/non-native-palms-planted-in-south-africa) and (2) "Non-native palms naturalised in South Africa" (https://www.inaturalist.org/projects/non-native-palms-naturalized-in-south-africa). Taxonomic identifications were verified and, where necessary, corrected for all records posted before the data cutoff date of 03 June 2026; the authors cannot guarantee the accuracy of identifications for records added to these projects after this date. The final

quality-filtered dataset generated and analysed during the current study has been archived on Zenodo (10.5281/zenodo.21806946).

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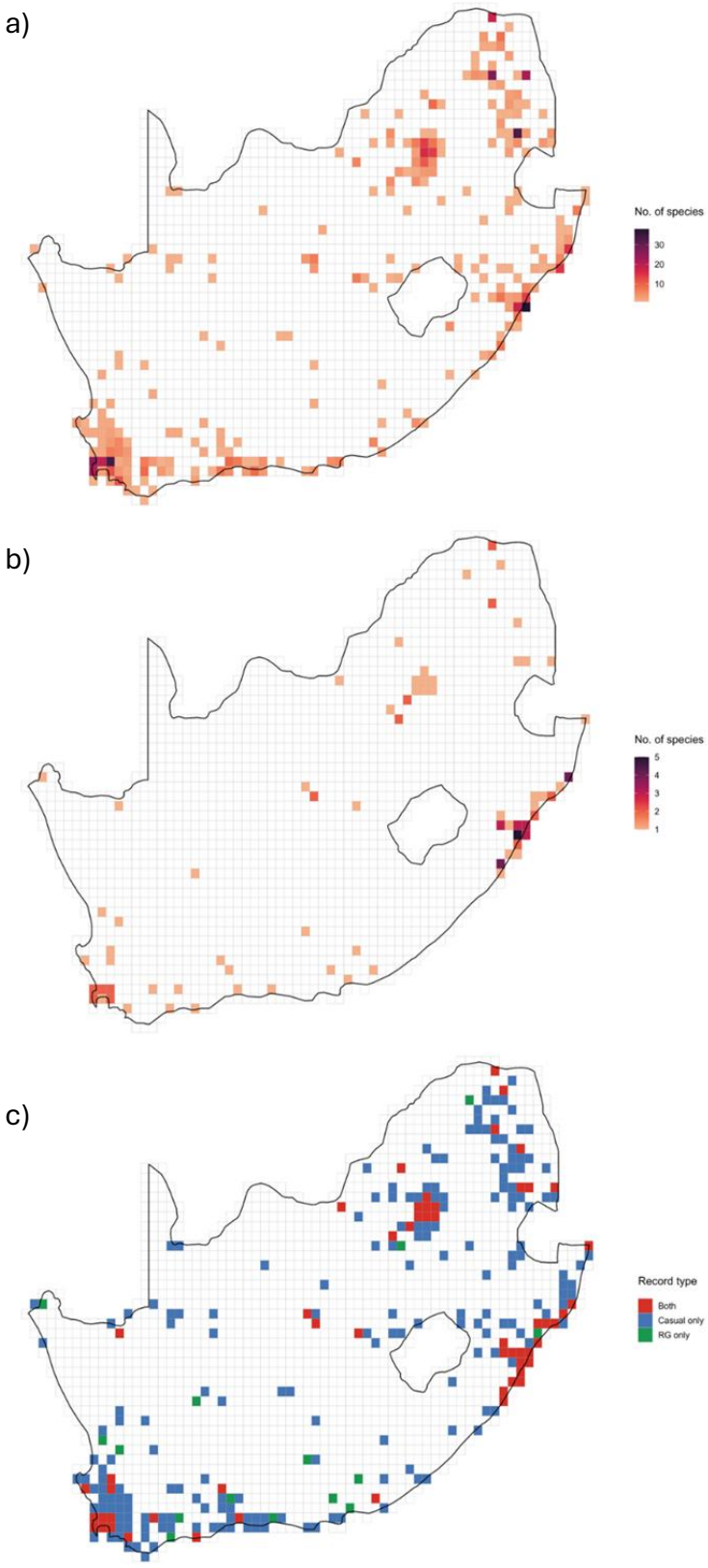
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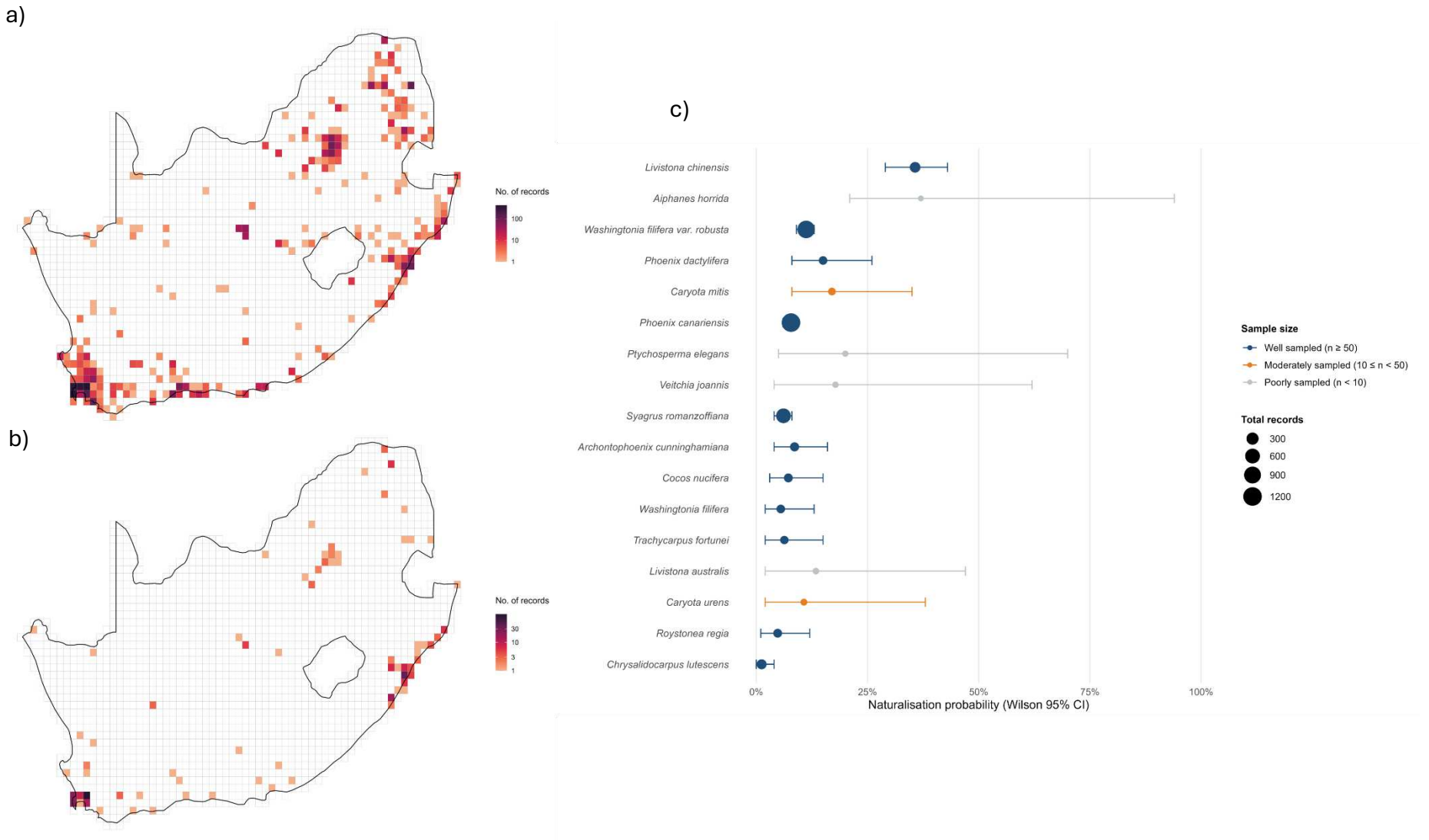
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1029 **FIGURES**



1030 **Fig. 1**. Species richness of non-native palms (Arecaceae) recorded in South Africa at the
1031 quarter-degree cell (QDC) level, based on iNaturalist observations. **(a)** Planted palm

species richness, based on Casual (cultivated) records, **(b)** naturalising palm species richness, based on Research Grade (wild-growing) records, and **(c)** distribution of record types per QDC, distinguishing cells with only Casual records (planted only), only Research Grade records (naturalising only), or both record types. QDCs with at least one Research Grade record were considered sites of confirmed or probable naturalisation. Darker colours in panels (a) and (b) indicate higher species richness. Maps were produced in R using the *sf* and *ggplot2* packages; the QDC grid shapefile was obtained from Zenodo (https://zenodo.org/doi/10.5281/zenodo.4457814).



1040 **Fig. 2**. Abundance of non-native palms (Arecaceae) recorded in South Africa at the quarter-degree cell (QDC) level, based on iNaturalist

observations. **(a)** Planted palm taxa abundance, based on Casual (cultivated) records, and **(b)** Naturalising palm taxa abundance, based on Research Grade (wild-growing) records. Darker colours indicate higher abundance; colour scales are log-transformed to account for the highly skewed distribution of records across QDCs. **(c)** Naturalisation probability for the 17 species with at least one Research Grade record, estimated using empirical Bayes shrinkage (Beta-binomial method of moments) with Wilson score 95% confidence intervals. Point size is scaled by total iNaturalist record count. Species are colour-coded by sample size: dark blue (well sampled, $n \geq 50$), orange (moderately sampled, $10 \leq n < 50$), and grey (poorly sampled, $n < 10$). Maps were produced in R using the sf and ggplot2 packages; the QDC grid shapefile was obtained from Zenodo (https://zenodo.org/doi/10.5281/zenodo.4457814).

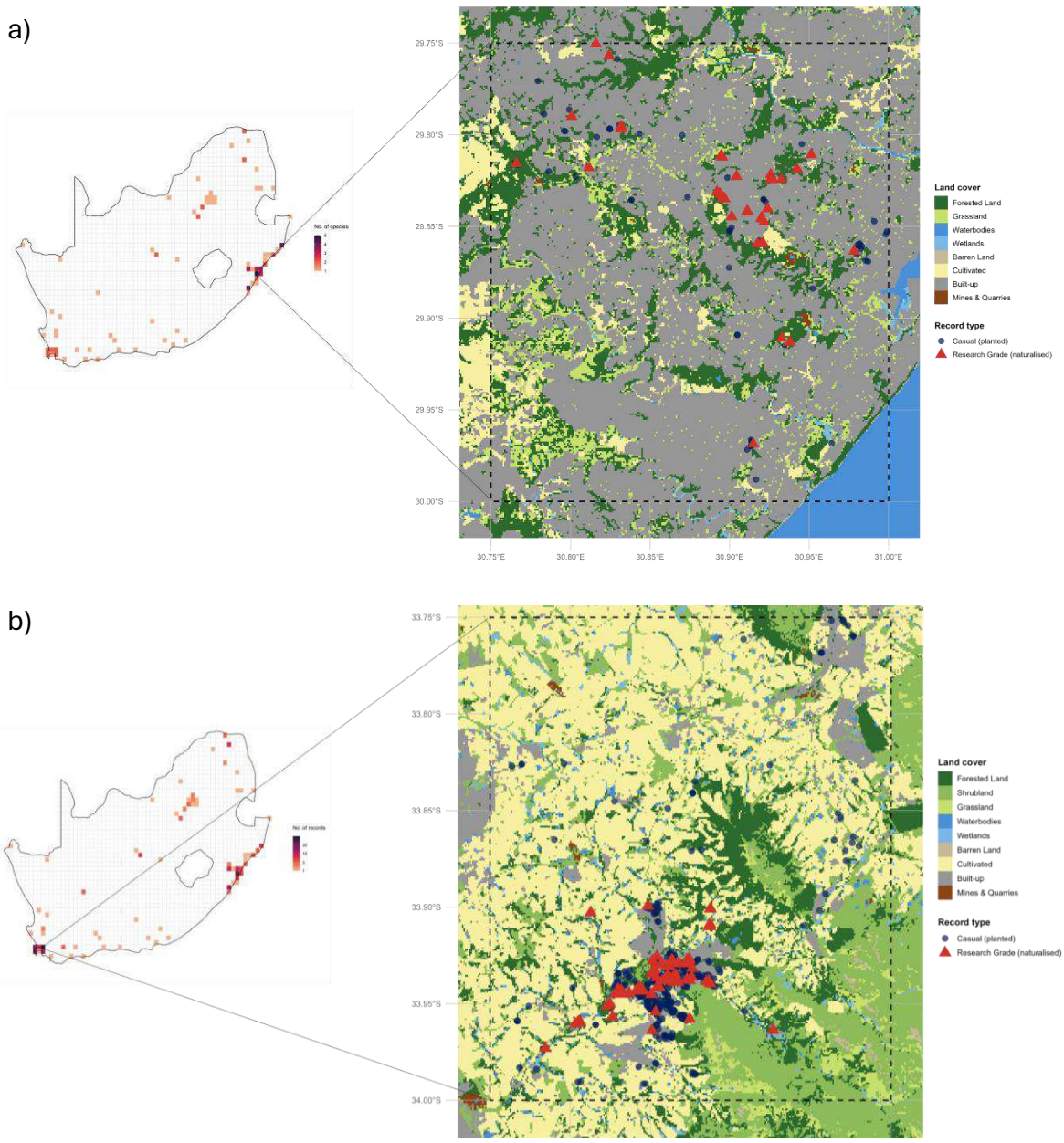
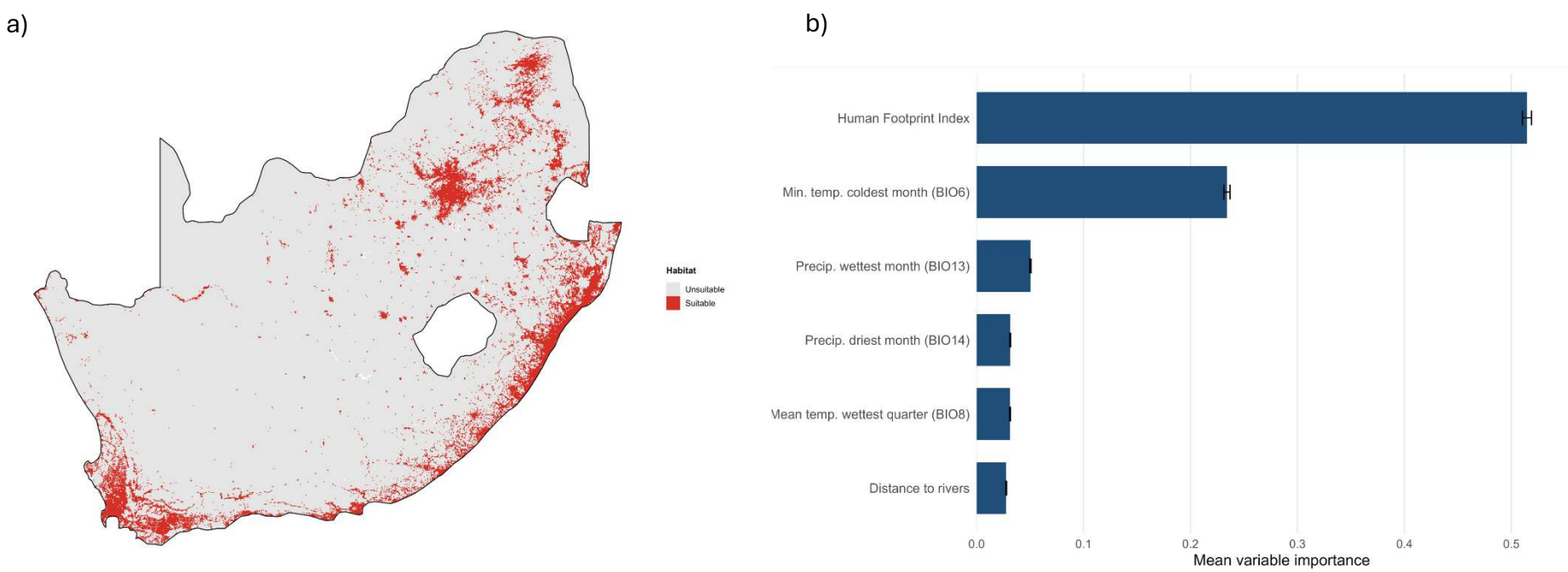
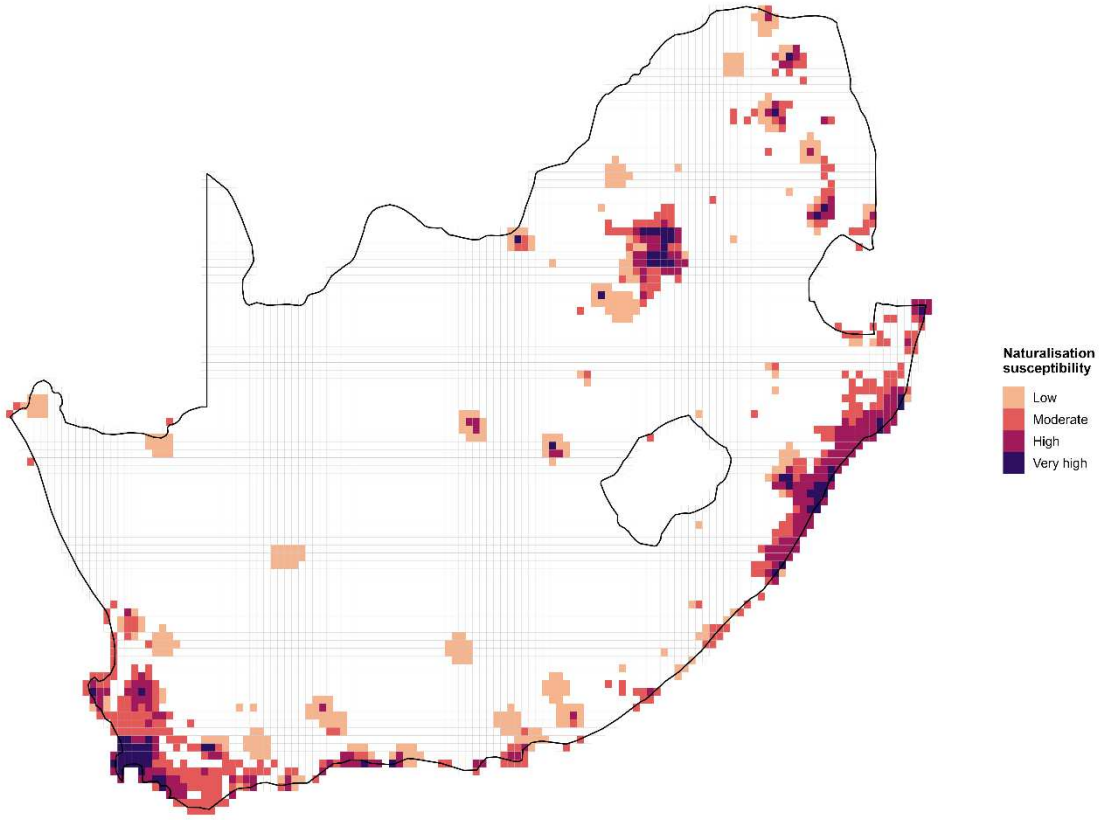


Fig. 3. Distribution of non-native palm (Arecaceae) records in the quarter-degree cell (QDC) with a) the highest naturalising palm species richness (Durban area, KwaZulu-Natal), and b) highest naturalising palm species abundance (Stellenbosch, Western Cape). Background land cover is derived from the South African National Land Cover dataset (SANLC 2022). The dashed border delineates the focal QDC boundary.



1054

1055 **Fig. 4**. Ensemble habitat suitability model for all (n=17) naturalising non-native palm species (Arecaceae) in South Africa. **(a)** Binary
1056 habitat suitability map showing areas predicted as suitable (red) or unsuitable (grey) for palm naturalisation. **(b)** Mean permutation
1057 variable importance (± SD) across all individual models.



Rank	QDC	Susceptibility score	Mean habitat suitability	Casual records	Planted species richness	RG records (naturalising)	RG species richness
1	E018S33DDC	0.94	0.85	334	28	85	2
2	E018S34ABB	0.92	0.84	318	15	22	2
3	E018S33CDD	0.90	0.82	306	25	17	1
4	E018S33DCC	0.78	0.89	167	17	3	1
5	E018S34BBA	0.72	0.84	126	12	11	2
6	E031S29CCA	0.71	0.89	104	38	5	3
7	E018S33DCA	0.67	0.81	91	10	4	1
8	E018S33DCB	0.64	0.83	58	11	1	1
9	E018S34ABA	0.64	0.80	64	17	1	1
10	E018S33DCD	0.63	0.87	36	10	1	1

Fig. 5. Naturalisation susceptibility map for non-native palms (Arecaceae) in South Africa at the level 3 quarter-degree cell (QDC) scale (±13 x 14 km). Susceptibility was assessed using three criteria: (1) habitat suitability ≥ 0.308 (TSS-optimised threshold), derived from an ensemble species distribution model (GLM, GBM, MaxEnt) evaluated using spatial block cross-validation; (2) propagule pressure, defined as ≥ 5 quality-filtered Casual (planted) iNaturalist records per QDC; and (3) proximity to the nearest existing naturalising population (≤ 25 km of the nearest quality-filtered Research Grade iNaturalist record). QDCs were classified as Very High (all three criteria met; n = 72), High (two criteria; n = 209), Moderate (one criterion, above-median composite score; n = 324),

or Low (one criterion, below-median composite score; n = 323). The table represents the ten highest priority QDCs for palm naturalisation susceptibility in South Africa, ranked by composite score.

TABLES

Table 1. List of non-native palm (Arecaceae) species recorded in South Africa with at least one iNaturalist record, with supplementary data from arboretum (Cheek et al. 2022) and herbarium (Glen 2002) sources. Species recorded only in arboreta, herbarium, or Glen (2002) sources without iNaturalist records are not included. QDC = number of level 2 quarter-degree cells in which each species has been recorded on iNaturalist. Naturalisation probability was estimated as the proportion of Research Grade (wild-growing) records relative to total iNaturalist records, adjusted using empirical Bayes shrinkage (Beta-binomial method of moments) to account for variation in sample size across species. Wilson score 95% confidence intervals are provided for each estimate (Wilson 1927; Brown et al. 2001). GloNAF status indicates whether a species is categorised for South Africa in the Global Naturalised Alien Flora database (GloNAF; van Kleunen et al. 2019). Taxa marked * are recorded as cultivated in South Africa by Glen (2002).

Taxa	QDC	Casual records	Research Grade records	Total iNaturalist records	Arboreta records	Herbarium records	Naturalisation probability	CI lower (95%)	CI upper (95%)	GloNAF status
Adonidia merrillii *	2	4	0	4	2	0	0	0	0.49	No
Aiphanes horrida *	2	1	2	3	1	1	0.37	0.21	0.94	No
Allagoptera caudescens *	1	1	0	1	0	0	0	0	0.79	No
Archontophoenix alexandrae *	13	24	0	24	4	0	0	0	0.14	No
Archontophoenix cunninghamiana *	28	77	7	84	7	4	0.086	0.04	0.16	No
Areca catechu *	1	1	0	1	0	0	0	0	0.79	No
Areca triandra *	2	2	0	2	0	0	0	0	0.66	No
Areca vestiaria	1	1	0	1	0	0	0	0	0.79	No
Arenga caudata *	2	3	0	3	0	0	0	0	0.56	No
Arenga hookeriana	1	1	0	1	0	0	0	0	0.79	No
Attalea cohune *	1	1	0	1	0	0	0	0	0.79	No
Attalea dubia	1	1	0	1	0	0	0	0	0.79	No
Beccariophoenix madagascariensis *	1	1	0	1	0	0	0	0	0.79	No
Bismarckia nobilis *	22	28	0	28	1	0	0	0	0.12	No
Brahea armata *	2	2	0	2	1	1	0	0	0.66	No
Butia capitata *	1	1	0	1	11	3	0	0	0.79	No

Butia odorata	20	42	0	42	0	0	0	0	0.08	No
Calyptronoma rivalis	1	1	0	1	0	0	0	0	0.79	No
Carpentaria acuminata *	2	2	0	2	2	0	0	0	0.66	No
Caryota mitis *	10	24	5	29	7	0	0.17	0.08	0.35	No
Caryota no *	2	2	0	2	0	0	0	0	0.66	No
Caryota urens *	8	10	1	11	6	2	0.107	0.02	0.38	No
Chamaedorea benziei	1	1	0	1	0	0	0	0	0.79	No
Chamaedorea brachypoda *	3	4	0	4	0	0	0	0	0.49	No
Chamaedorea cataractarum *	3	4	0	4	0	0	0	0	0.49	No
Chamaedorea costaricana *	4	4	0	4	0	0	0	0	0.49	No
Chamaedorea elatior *	1	1	0	1	0	1	0	0	0.79	No
Chamaedorea elegans *	10	27	0	27	1	0	0	0	0.12	No
Chamaedorea geonomiformis *	1	1	0	1	0	0	0	0	0.79	No
Chamaedorea glaucifolia *	1	1	0	1	0	0	0	0	0.79	No
Chamaedorea hooperiana	1	1	0	1	0	0	0	0	0.79	No
Chamaedorea klotzschiana *	1	1	0	1	0	5	0	0	0.79	No
Chamaedorea metallica *	4	4	0	4	0	1	0	0	0.49	No
Chamaedorea microspadix *	5	5	0	5	0	4	0	0	0.43	No
Chamaedorea oreophila	1	1	0	1	0	0	0	0	0.79	No
Chamaedorea plumosa	2	2	0	2	1	0	0	0	0.66	No
Chamaedorea radicalis *	1	1	0	1	0	0	0	0	0.79	No
Chamaedorea seifrizii *	10	14	0	14	0	1	0	0	0.22	No
Chamaedorea tepejilote *	3	3	0	3	2	5	0	0	0.56	No
Chamaerops humilis *	30	110	0	110	8	7	0	0	0.03	No
Chambeyronia macrocarpa *	4	4	0	4	0	0	0	0	0.49	No
Chrysalidocarpus decaryi *	26	47	0	47	6	0	0	0	0.08	No
Chrysalidocarpus decipiens *	1	1	0	1	0	0	0	0	0.79	No
Chrysalidocarpus lanceolatus	1	1	0	1	1	0	0	0	0.79	No
Chrysalidocarpus lutescens *	39	130	1	131	6	2	0.012	0	0.04	No
Chrysalidocarpus madagascariensis *	3	4	0	4	5	1	0	0	0.49	No

Chrysalidocarpus onilahensis	1	1	0	1	0	0	0	0	0.79	No
Cocos nucifera *	22	69	5	74	3	2	0.072	0.03	0.15	No
Copernicia alba	1	1	0	1	0	0	0	0	0.79	No
Copernicia prunifera *	1	1	0	1	2	1	0	0	0.79	No
Corypha umbraculifera *	1	1	0	1	0	0	0	0	0.79	No
Corypha utan	1	1	0	1	1	0	0	0	0.79	No
Dictyosperma album *	5	8	0	8	1	0	0	0	0.32	No
Elaeis guineensis *	3	3	0	3	2	0	0	0	0.56	No
Euterpe edulis *	1	1	0	1	0	0	0	0	0.79	No
Gaussia maya *	1	1	0	1	1	0	0	0	0.79	No
Howea belmoreana *	2	2	0	2	0	0	0	0	0.66	No
Howea forsteriana *	13	20	0	20	5	1	0	0	0.16	No
Hyophorbe indica *	1	1	0	1	0	0	0	0	0.79	No
Hyophorbe lagenicaulis *	10	18	0	18	3	0	0	0	0.18	No
Hyophorbe verschaffeltii *	16	25	0	25	3	0	0	0	0.13	No
Johannesteijsmannia altifrons	1	2	0	2	0	0	0	0	0.66	No
Johannesteijsmannia magnifica	1	1	0	1	0	0	0	0	0.79	No
Jubaea chilensis *	1	1	0	1	1	0	0	0	0.79	No
Laccospadix australasicus *	1	1	0	1	0	0	0	0	0.79	No
Latania loddigesii *	2	2	0	2	1	0	0	0	0.66	No
Licuala grandis *	3	4	0	4	1	2	0	0	0.49	No
Licuala spinosa *	1	1	0	1	0	0	0	0	0.79	No
Livistona australis *	6	7	1	8	3	1	0.134	0.02	0.47	No
Livistona benthamii	1	1	0	1	0	0	0	0	0.79	No
Livistona chinensis *	52	113	64	177	15	4	0.357	0.29	0.43	Naturalised
Livistona decora *	3	3	0	3	1	1	0	0	0.56	No
Livistona muelleri *	1	1	0	1	0	0	0	0	0.79	No
Livistona nitida	2	2	0	2	0	0	0	0	0.66	No
Livistona saribus *	1	1	0	1	0	0	0	0	0.79	No
Lodoicea maldivica *	1	1	0	1	0	0	0	0	0.79	No

Marojejya darianii *	1	1	0	1	0	0	0	0	0.79	No
Normanbya normanbyi *	1	1	0	1	0	0	0	0	0.79	No
Parajubaea cocoides *	2	2	0	2	0	0	0	0	0.66	No
Phoenicophorium borsigianum *	1	1	0	1	0	0	0	0	0.79	No
Phoenix canariensis *	113	1110	93	1203	24	0	0.078	0.06	0.09	Invasive
Phoenix dactylifera *	36	51	9	60	7	1	0.15	0.08	0.26	Invasive
Phoenix roebelenii *	31	95	0	95	5	1	0	0	0.04	No
Phoenix sylvestris *	2	2	0	2	1	3	0	0	0.66	No
Pinanga coronata *	1	1	0	1	2	2	0	0	0.79	No
Pritchardia hillebrandii *	1	1	0	1	0	0	0	0	0.79	No
Ptychosperma elegans *	2	3	1	4	1	0	0.2	0.05	0.7	No
Ptychosperma propinquum *	2	3	0	3	1	0	0	0	0.56	No
Raphia farinifera *	1	2	0	2	1	0	0	0	0.66	No
Ravenea glauca	2	2	0	2	0	0	0	0	0.66	No
Ravenea hildebrandtii	1	1	0	1	0	0	0	0	0.79	No
Ravenea rivularis	5	5	0	5	0	0	0	0	0.43	No
Rhapis excelsa *	14	22	0	22	3	5	0	0	0.15	No
Rhapis humilis *	3	3	0	3	0	0	0	0	0.56	No
Roscheria melanochaetes	1	1	0	1	0	0	0	0	0.79	No
Roystonea oleracea *	3	3	0	3	0	0	0	0	0.56	No
Roystonea regia *	34	68	3	71	6	3	0.048	0.01	0.12	No
Sabal mauritiiformis *	1	1	0	1	0	0	0	0	0.79	No
Sabal mexicana *	7	15	0	15	2	0	0	0	0.2	No
Sabal palmetto *	1	3	0	3	5	0	0	0	0.56	No
Saribus rotundifolius *	1	2	0	2	0	0	0	0	0.66	No
Serenoa repens *	1	2	0	2	1	0	0	0	0.66	No
Syagrus oleracea *	1	1	0	1	0	1	0	0	0.79	No
Syagrus picrophylla	1	1	0	1	0	0	0	0	0.79	No
Syagrus romanzoffiana *	102	549	35	584	26	0	0.061	0.04	0.08	No
Syagrus vermicularis	1	1	0	1	0	0	0	0	0.79	No

Syagrus weddelliana *	3	4	0	4	0	0	0	0	0.49	No
Thrinax parviflora *	1	1	0	1	2	0	0	0	0.79	No
Thrinax radiata *	2	2	0	2	0	0	0	0	0.66	No
Trachycarpus fortunei *	26	50	3	53	10	3	0.063	0.02	0.15	No
Veitchia joannis *	5	4	1	5	1	0	0.178	0.04	0.62	No
Verschaffeltia splendida *	1	2	0	2	1	0	0	0	0.66	No
Washingtonia filifera *	22	59	3	62	12	1	0.055	0.02	0.13	No
Washingtonia filifera var. robusta *	126	893	113	1006	16	1	0.112	0.09	0.13	Invasive
Wodyetia bifurcata *	8	9	0	9	2	2	0	0	0.3	No

Naturalisation probability is reported as zero for species with no Research Grade records. For these species, the Wilson confidence interval upper bound indicates the maximum naturalisation probability that cannot be excluded given the available sample size.

SUPPLEMENTARY MATERIAL

Online Resource 1. Summary of quality-filtered iNaturalist records for non-native palm (Arecaceae) taxa in South Africa. Records were filtered to include only those with a reported positional accuracy ≤ 500 m, at least one identification agreement, and coordinates falling within the South African mainland boundary. The numbers in brackets show the percentage of the total. *Records and taxa retained for spatial analyses (species-level only).

General		
Number of observers	1355	
Date range for records	2002–2026	
All filtered records by taxonomic rank		
Records at genus level	88	(2.0)
Records of species	**4220**	(97.2)
(Records of hybrids)	35	(0.8)
Total filtered records	**4343**	
Unique taxa by rank		
Taxa at genus level	11	(8.4)
Taxa at species level*	118	(90.1)
(Hybrid taxa)	2	(1.5)
Total taxa	**131**	
Quality grade (all filtered records)		
Casual (planted)	3985	(91.8)
Research Grade (wild-growing)	358	(8.2)
Records retained for spatial analyses (species-level only)*		
Total records*	**4220**	
Casual (planted)*	3873	(91.8)
Research Grade (wild-growing)*	347	(8.2)
Unique species*	118	
Identification agreements		
Mean agreements per record	1.6	
Median agreements per record	2	
Maximum agreements	5	
Identification disagreements		
Mean disagreements per record	0.03	
Median disagreements per record	0	
Maximum disagreements	2	
Records with ≥ 1 disagreement	116	(2.7)

Species counts in this table reflect original iNaturalist taxonomy (118 species). After alignment to the World Checklist of Vascular Plants (WCVP; Govaerts et al. 2021), three synonyms were merged, yielding 115 accepted species used in all subsequent analyses.

Online Resource 2. Validation performance metrics for individual algorithms and ensemble models used in the habitat suitability model for naturalised palms in South Africa. Individual algorithm values are means (± SD) across 12 model runs (3 pseudo-absence datasets × 4 spatial block cross-validation folds; Roberts et al. 2017). 10,000 background points were generated per pseudo-absence dataset. TSS = True Skill Statistic; AUC = area under the receiver operating characteristic curve. GAM and RF were excluded from the ensemble due to poor spatial transferability (mean validation TSS < 0.5). The final ensemble comprised GLM, GBM, and MaxEnt only.

Algorithm	n	TSS (mean)	TSS (SD)	AUC (mean)	AUC (SD)	Sensitivity (%)	Specificity (%)	Cutoff
Individual algorithms (spatial block cross-validation)								
GLM	12	0.662	0.079	0.943	0.017	90.6	93.5	583
GBM	12	0.649	0.182	0.939	0.025	92.7	93.9	566
MAXNET	12	0.614	0.139	0.932	0.029	90.3	94.4	131
GAM	12	0.484	0.252	0.819	0.089	96.5	92.3	431
RF	12	0.279	0.204	0.922	0.031	100.0	100.0	369
GAM and RF excluded from ensemble (mean validation TSS < 0.5)								
Ensemble models (GLM + GBM + MaxEnt)								
EMmean (unweighted)	—	0.849	—	0.972	—	93.2	91.7	305
EMwmean (TSS-weighted)	—	0.853	—	0.972	—	93.8	91.6	308

Ensemble TSS and AUC are calibration (full-dataset) metrics. Individual algorithm values are spatial block cross-validation metrics, providing more conservative estimates of predictive performance.