Title page

Title: Exotic Hobos: Release, escape, and potential secondary dispersal of African red-headed agamas (*Agama picticauda* PETERS, 1877) through the Florida railway systems.

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Acknowledgements: Not applicable

Abstract:

Invasive species are introduced and established through a variety of distribution channels, and can cause detrimental side-effects to native ecosystems. Understanding the origins and spread of non-native species can assist in creating informed management decisions to prevent future introduction and to remove established populations. By employing geographic profiling, a technique commonly used for criminal investigations, along with suspected origin locations of introduced African red-headed agamas (*Agama picticauda*) provided by previous studies, potential origins of agama sub-populations and observation points were generated and confirmed throughout Florida. The results of this study indicate that African red-headed agamas likely established themselves through both release, and escape, while also potentially hitchhiking on plant exports, and dispersing throughout Florida via the railway systems.

Keywords:

Geographic profiling, Invasive species, Florida, African red-headed agama, Railways

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Availability of data and material (data transparency)

Exotic Hobos: Exotic Hobos: Release, escape, and potential secondary dispersal of African red-headed agamas (*Agama picticauda* PETERS, 1877) through the Florida railway systems.

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ABSTRACT

Invasive species are introduced and established through a variety of distribution channels, and can cause detrimental side-effects to native ecosystems. Understanding the origins and spread of non-native species can assist in creating informed management decisions to prevent future introduction and to remove established populations. By employing geographic profiling, a technique commonly used for criminal investigations, along with suspected origin locations of introduced African red-headed agamas (*Agama picticauda*) provided by previous studies, potential origins of agama sub-populations and observation points were generated and confirmed throughout Florida. The results of this study indicate that African red-headed agamas likely established themselves through both release, and escape, while also potentially hitchhiking on plant exports, and dispersing throughout Florida via the railway systems.

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INTRODUCTION

Florida currently has the largest number of invasive and introduced reptile species in the United States (Bartlett and Bartlett 1999; Butterfield et al. 1997; EDDMapS, 2012; Engeman et al. 2011). One species, the African red-headed agama, is known to be established throughout several counties of Florida (Enge et al. 2004). Previously thought to be *Agama agama africana* Hallowell, 1844 (Harris, 1964) or *Agama agama*, Linnaeus 1758 (Wilson and Porras 1983), phylogenetic study by Nuñez et al. (2016) revealed that the introduced Florida agama populations are more likely to be the African red-headed agama (*Agama picticauda* PETERS, 1877).

African red-headed agamas are semi-arboreal, and thrive in urban environments within both their native and introduced ranges (Akani et al. 2013; Enge et al. 2004; Luiselli et al. 2011; Yeboah, 1982). Although their diet is primarily insectivorous, they are opportunistic omnivores that have been documented eating fruit and discarded anthropogenic food items (Akani et al. 2013; Anibaldi et al. 1998; Chapman and Chapman, 1964; Harris, 1964; Ofori et al. 2018; Yeboah, 1982). Agamas often take shelter in nearby objects, crevices, and structures upon approach by humans, to avoid unfavorable weather conditions, and for protection against predation attempts (Enge et al 2004; Cloudsley-Thompson 1981).

The first records of agamas in Florida appeared as far back as the mid-1970's with voucher specimens (LSUMZ 36647, UF 43490) collected from a population thought to be eliminated by the demolition and subsequent building of a railway system (Enge et al. 2004; Wilson and Porras, 1983). The re-emergence of agama populations throughout Florida took place around the late 1980s to early 2000s where some individuals were expected to have been released after breeding facilities or exotic pet shops were destroyed by hurricane Andrew, while others may have been escaped pets, or released into the wild intentionally (Enge et al. 2004). Currently, there have been observations of A. *picticauda* in 17 Florida counties (Figure 1); some of which are assumed to have been isolated incidents, others which are established sub-populations. Although many origins of the African red-headed agamas in Florida are

either assumed to be specific locations, or have been communicated by confession of the responsible individual (Enge et al. 2004), there have been no attempts so far to use modelling methods for determining the accuracy of these assumed origins.

Geographic profiling is a technique which is used most often in forensic science and criminology by modelling the spatial locations of crimes in order to identify the origin location from which a criminal is operating (Rossmo 1999; Rossmo et al. 2014). Since its original use, geographic profiling has been modified and applied to infectious disease models (Verity et al. 2014), ecology (Faulkner et al. 2015; Faulkner et al. 2017), and wildlife criminology (Faulkner et al. 2018; Romanach et al. 2019), where locations of committed crimes are instead substituted with sites of infection, animal observations records, and suspected poaching locations. The geographic profiling algorithm uses coordinate locations of points of interest (e.g. locations of a crime), and through a Bayesian framework, clusters the coordinates to locate an "anchor point" or suspected epicenter (e.g. location where a criminal operates) while providing a "hitscore" or accuracy for suspect locations (O'Leary, 2009).

In this study, I use African red-headed agamas occurrence records retrieved from the Early Detection & Distribution Mapping System or EDDMapS (EDDMapS 2012) from Florida and implement geographic profiling models in an attempt to find release location origins, using the earliest sighting records, and suspected origins from the literature. In consideration of trends in the modelled origins, I discuss the implications of my findings and suggest potential management decisions.

METHODS

Data

All records of *Agama picticauda* were queried from EDDMapS (EDDMapS 2012). Records with no coordinates were dropped from the data set, and coordinates which fell outside of the Florida state

shapefile were masked from the data. After manual quality control checks of the data, 194 observations encompassed by 17 Florida counties remained and were used in the analysis (Figure 1).

Analysis

All analyses were carried out using R statistical software version 3.6.3 (R Core Team 2020). Suspected release locations (n=6), as well as the earliest observation record (n=1) (Table 1) were used in the geographic profiling model by employing the R package "RgeoProfile" (Verity 2015), the sigma mean (i.e. the mean prior standard deviation of dispersal distribution in km) was set to 0.5 as the noted dispersal distance of a >10-year sustained population by Enge et al. (2004); all other parameters were set to the function default with weakly informative priors; prior and posterior distributions were plotted and analyzed for abnormalities before proceeding. HitScores (HS) were recorded for each suspect location; higher HS indicated low probability of the suspected origin, while lower HS indicates the suspected is more likely to be the true origin. Centroids of suspected origin areas were analyzed on Google Maps within a 5 km radius to examine any evident trends in the surroundings (e.g. businesses, housing, land use, transportation routes, etc.). Euclidean distance from points of interest were then calculated in a post-hoc analysis to categorize modelled origin locations. After the initial analysis, railway shapefiles were downloaded from the US Bureau of Transportation Statistics (BTS 2020) based on modelled location trends. Other auxiliary R packages were used for data organization and visualizations (Supplementary file I)

Due to discrepancies in modelled origin location trends (abundance of proximal exotic plant exporters), a subset of the total observation data was created to only include records from south Florida below decimal latitude 27.0° N. The subset of data was then divided into two groups: group one included observed locations (n=49) between 2002 and 2015 (with the single voucher record from 1975), group two included the locally suspected origin locations: a) Coral Castle (Pers. Comm.), and b) the location of a

reptile dealers' home which was apparently destroyed in hurricane Andrew (Enge 2004). The model was run again with the subset and new modelled origin locations were analyzed.

RESULTS

Overall Geographic Profile

The overall model generated 46 modelled origin locations for the sub-populations of A. *picticauda* throughout Florida, with an immediately evident trend of proximity and relationship to the Florida railway systems with outward dispersal from metropolitan areas being the most recent records (Figure 1). Out of the modelled locations, three locations were a complete match with the suspected origins: 1) the reptile dealer, whose house was suspected to have been destroyed during hurricane Andrew (HS = 0.002), 2) the earliest observation of A. *picticauda* at the Inter-Rail Transport of Miami HS = 0.086, and the release at the private residence in Punta Gorda (HS = 0.003), all other suspected locations were closely matched with the modelled origin locations (Relocated reptile dealer, HS = 1.393; Coral Castle, 0.982; Strictly Reptiles, HS = 0.023), except for the suspected location of the Orange Country reptile store release provided as a personal communication in Enge et al. (2004) (HS = 39.1558).

Trends in modelled origin locations were divided into five categories: 1) Escaped or released (locations proximal to pet shops, reptile breeders/rescue centers, and locations which had no association with the other categories; n = 16), 2) Exotic plants (locations that were <1km from exotic plant nurseries, importers, or exporters; n = 4), 3) Possible hitchhiker (2-5 km from railroads, which assumedly travelled from the railroad to the current location via another vehicle), 4) Railway locations (locations proximal to railways, most points were < 2 km from railways), and 5) Suspect complete match (locations which fell <1km of their suspected origin; n = 3). Railroad locations had a mean Euclidean distance of 581.96 m, with a minimum of 13.27 m (observations themselves were directly over the railroad) and a max distance of 1.98 km. Mean Euclidean distance from suspect location matches was 388.38 m, with a minimum of 0

m (the original observation of A. *picticauda* from the Inter-Rail Transport of Miami), and a max of 691.02 m (location proximal to the homestead reptile breeder's house which was destroyed by hurricane Andrew). All exotic plant locations were <0.5 km from the modelled origin location.

South Florida Geographic Profile

Due to the prominence of several sub-populations without connectivity, the model produced 18 potential origin locations (Figure 3). Upon examination of areas surrounding the location outputs, there was an evident trend in nurseries, importers, and exporters of exotic plants within 0.5 km of the suspected origin locations (72%). Over half of the points fell within railway locations ~1 km or less from railroads. The model produced a HS of 2.712 for Coral Castle, and HS of 0.190 for the destroyed reptile breeders house near the junction of Coconut Palm Drive (SW 248th Street) and SW 163rd Avenue as the primary suspects, thus indicating the most likely origin to be the destroyed reptile breeders house of the two potential locations of origin.

DISCUSSION

Sustained sub-populations in central and north Florida were not reported until the late 1980s to early 2000s (Enge et al. 2004). However, African red-headed agamas have documented occurrences in south Florida as early as 1975, the first of which was found in south Florida on top of what is now the Inter-Rail Transport of Miami (Enge et al. 2004; Wilson and Porras 1983; EDDMapS, 2012). Given the typically small dispersal rate of the known subpopulations (~0.5 km), the agama's ranges aren't likely to be greatly expansive from their points of origin via unassisted dispersal. This leads me to believe that the subpopulation in 1975 was not extirpated, but rather persisted unmanaged, and migrated through the railway system.

That being said, some sub-populations were likely also formed from escaped or released animals from breeders, dealers, or reptile-based, pet owners, or facilities; many of which were also located near railways. The model indicated that likely origins of a few sub-populations were the location of a reptile dealers' home in Redlands, which was destroyed during hurricane Andrew in south Florida, as well as the location of a reptile store near Hollywood, Florida. Additionally, there was a high model accuracy over the suspected private residence in Punta Gorda which was reported to have released several individuals by Enge et al. (2004), thus confirming this location of origin. Another suspect location in south Florida fell within close proximity to the Zoological Wildlife Foundation (ZWF) Miami Venue, which has been operating since 2001 (Florida Department of State 2020). This location is relatively distant from any railways in comparison to the majority of others, and houses several exotic reptile species as well as exotic plants which could have harbored hitchhiking individuals, or could have had an incident of an escaped animal. Another modelled location fell between several observations directly on top of Central Florida Reptiles and Rescue in North Harbor City, although the observations themselves were lining the railways. Whether or not this facility participated in their spread is uncertain; still, it was interesting to see as the epicenter of the points generated by the model.

Several points in various counties were scattered with single observations on houses and locations which were away from railroad tracks and exotic plant importers/exporters, which indicates these may have been released intentionally. It has been documented that some reptile owners will release lizards to build populations to capture and sell later on (Krysko et al. 2003). However, given that agamas tend to do poorly in captivity (Harris 1964), and are relatively inexpensive to purchase (Enge et al. 2004), some pet owners may simply release the animals to avoid caring for them.

While inspecting the immediate areas surrounding the modelled origins in south Florida, there was an abundant trend of modelled locations which fell near exotic plant nurseries and exporters, mostly fruit trees and orchids. One point fell over top of the sorting facility of the Florida Department Agriculture and Consumer Services (Division of Plant Industry), which sorts through imported exotic plants and

attempts to control insects and pests which may negatively affect native Florida species (FDACS 2020). This brings into question whether there was an incident at the facility where imported plants from one of the African countries, in which these lizards are native, may have hitchhiked on an imported plant and subsequently escaped. The Fairchild Tropical Botanic Garden sub-population may have been an extension of that possible release scenario, or simply a result of hitchhiking agamas on plants they imported.

After the phylogenetic verification by Nuñez et al. (2016), building on the list of native nations by Enge et al. (2004), it was concluded that the introduced agamas' native ranges potentially include: Benin, Ghana, Togo, Liberia, Ivory Coast, Niger, Cameroon, Democratic Republic of the Congo, and Gabon. Nuñez et al. (2016) also reported that the genetic variation in sub-populations indicates that multiple introductions were likely. This could indicate that both imported shipments, either of the animals themselves as exotic pets, or of plants from these countries which the animals take shelter in are potentially high-risk introductory origins. Based on the locations produced by geographic profiling, south Florida observations appear to be connected to areas with nearby exotic plant nurseries/exporters and railways outside of the suspected ranges of introduction, confirming the likelihood of plant affiliated introductions. Furthermore, nearly all of the recorded observations outside of major metropolitan areas occurred within close proximity to railways, or in shipping yards and warehouses in which they pass through. Also worth noting is that observations in metropolitan areas typically occurred earlier (<2012) than the more recent observations (>2012) outside of them. This implies that the railways are acting as a dispersal agent which may establish agmas via secondary introduction.

Due to their ambiguous diet (Akani et al. 2013; Anibaldi et al. 1998; Chapman and Chapman, 1964; Harris, 1964; Ofori et al. 2018; Yeboah, 1982), and tendency to take shelter in various structures (Enge et al. 2004; Cloudsley-Thompson 1981), it makes sense that the agamas are would unintentionally hitch rides on the railways to other locations. Some notable areas in which the model pinged as the epicenter of observations along the railways included Cemex factories, tropical fruit exporters, exotic plant exporters, and grocery warehouses. The Cemex factories likely picked up hitchhiking individuals

sunning themselves or sheltering in their product shipments, as they often tend to utilize man-made debris for perching and shelter (Enge et al. 2004; Grandison, 1968). Fruit exporters, grocery warehouses, and exotic plant exporters have an abundance of insects (e.g. pollinators, flies, ants) which may subsist on their shipped and discarded product and would otherwise be a sustainable food source for the agamas. South Florida also has several bee farms which fall within close proximity the some of the agama subpopulations; one homestead bee farm near the railway has a thriving population (Pers. Obs.). Interestingly enough, the northernmost observations near Jacksonville also fall within close proximity to bee farms. Whether or not this is coincidence is uncertain; however, agamas being imported with bee farm related products is also a feasible explanation for the occurrences.

The limitations of geographic profiling with occurrence data should be noted, as the clustering technique cannot identify clusters with relatively isolated points. Some of the suspected origin locations in the model were produced as the occurrence location itself in cases of coordinate isolation, which means that inferences were made based on the surroundings of the occurrence point itself and not necessarily an anchor point generated by the algorithm. Nonetheless, each point was taken into account, and most of them followed the same trends as the suspected origin locations generated by the clustered anchor points.

In conclusion, geographic profiling is an invaluable technique which can be applied over a wide range of ecological investigations in order to locate potential points of origin and persons of interest (Faulkner et al. 2015; Faulkner et al. 2017; Faulkner et al 2018; Romanach et al. 2019; Verity et al. 2014). These models can be used by both ecologists and law enforcement agencies to generate a list of potential suspects to investigate, and create risk-management guidelines to effectively combat the spread of established invasive species and predict potential high-risk areas for the prevention of future introductions. More importantly, species observation records have been shown to uphold accuracy in geographic profiling models in comparison to the expensive, and otherwise time-consuming trapping approaches (Faulkner et al. 2017), which outlines the importance of open citizen-science data, and open science in general.

The implications of the findings in this study are not only applicable to Florida, as African red-headed agamas appear to be occupying a mode of transportation which is connected nationwide, and not only applicable to the species in question, as others species have the potential to hitchhike on shipped items and travel in the same manner (Rochford et al. 2015). Railways and other transportation corridors are known sources of travel and establishment of invasive species populations (Van Der Windt and Swart 2008). Along with globalization of trade and shipping, invasive species being imported as stowaways (Hulme 2009) and through the pet trade (Perrings et al. 2005) becomes increasingly more prominent. Although the survival and spread of African red-headed agamas in other states may rely on their thermal tolerance, the structures and debris they use for shelter may allow them to survive cold temperatures for prolonged periods of time (Enge et al. 2004). Considering the potential of fruit exports, such as citrus, from Florida to other states and even other countries, the potential of agamas establishing themselves at warehouse locations along railways and ports of entry is increasingly likely. In order to effectively manage the spread of African red-headed agamas and other hitchhiking invasive taxa within their potentially habitable ranges, sub-populations within proximity to railways and ports of entry with transportation corridors should be targeted and effectively removed.

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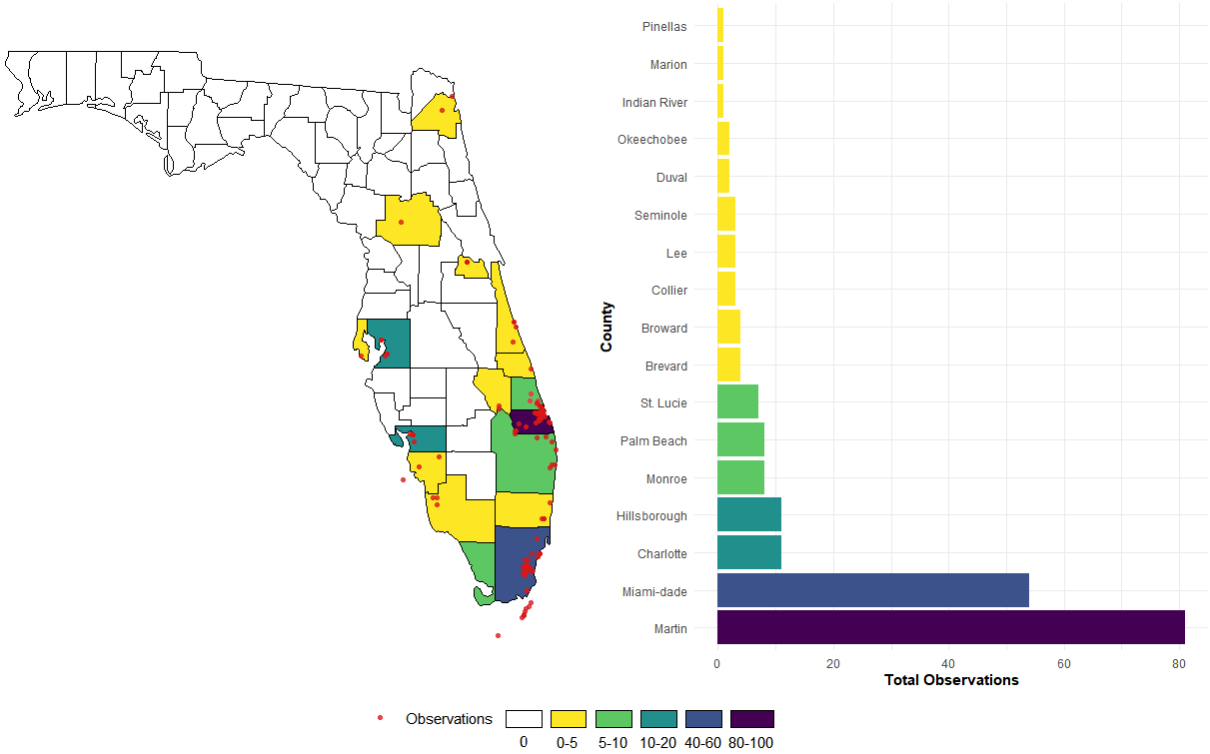


Figure 1. Total number of A. *picticauda* observations from EDDMaPS per Florida county between 2002 – 2015 (with the exception of a single 1975 specimen from Miami-Dade County; n = 194).

Table 1. Locations of all suspected origins used in the geographic profile model and respective HS values (low = accurate, high = inaccurate). An asterisk * was placed next to locations used in the south Florida subset model.

Suspected origin	Longitude	Latitude	Year	Authority
Reptile dealer residence *	-80.4556	25.53618	1992	Enge 2004
Reptile dealer relocated	-80.3199	27.13011	1999	Enge 2004; powell, 2003
Coral castle *	-80.4443	25.50054	1992	Pers. Comm.
A. *picticauda* (Earliest observation)	-80.3114	25.837	1975	EDDMapS
Strictly reptiles	-80.2195	26.04573	1989	Enge 2004
Private residence	-82.0305	26.94154	1987	Clark 2003
Released from reptile store	-81.1684	28.4618	2000	Enge 2004

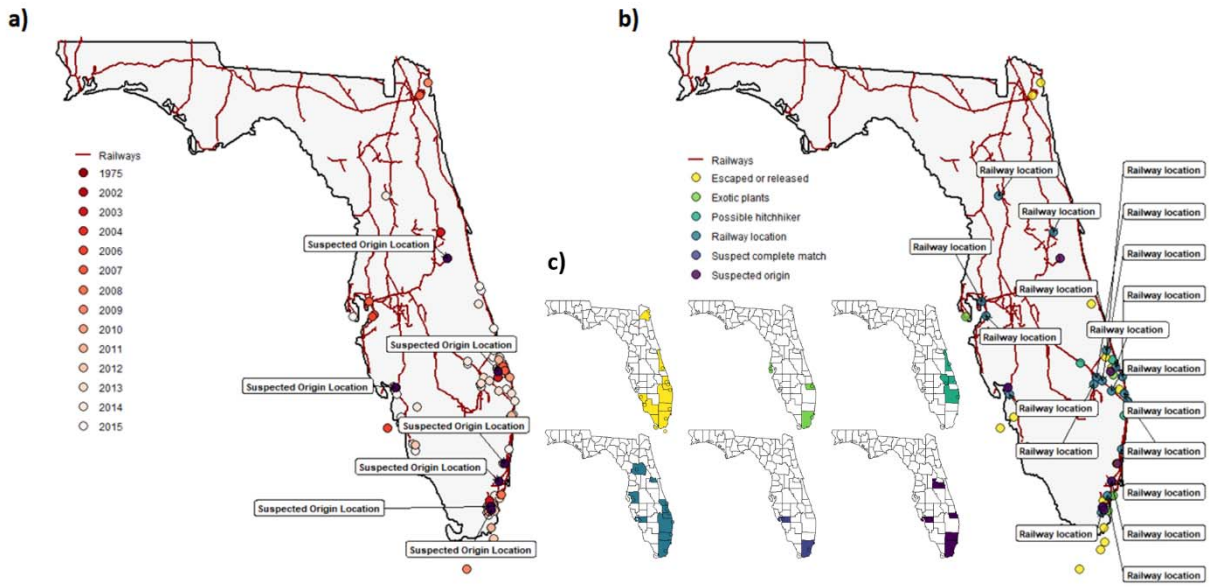


Figure 2. a) all observations of A. *picticauda* used in the model (n=194) colored by associated year of observation (white = recent record; dark red = older record), with locations of the seven suspected origins (dark purple); **b)** origins outputted by geographic profile (n = 46) model colored by category with emphasis on railway locations (n = 19); **c)** Florida maps with counties filled based on diaspora of each release origin category.

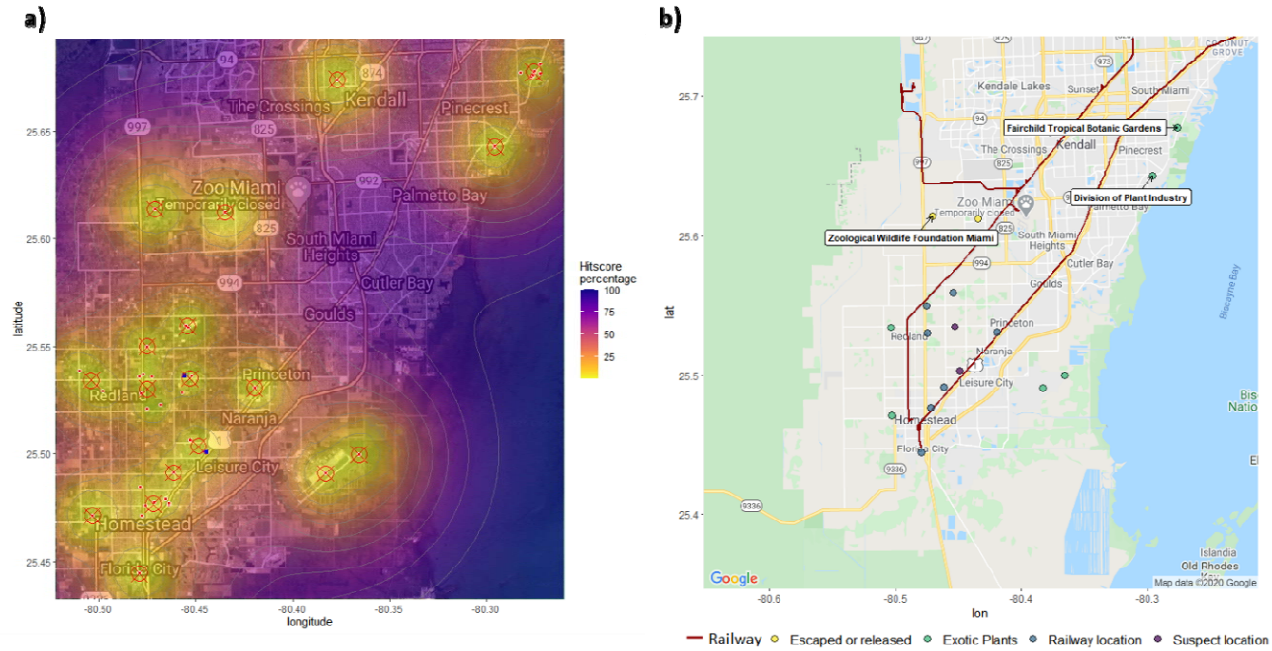
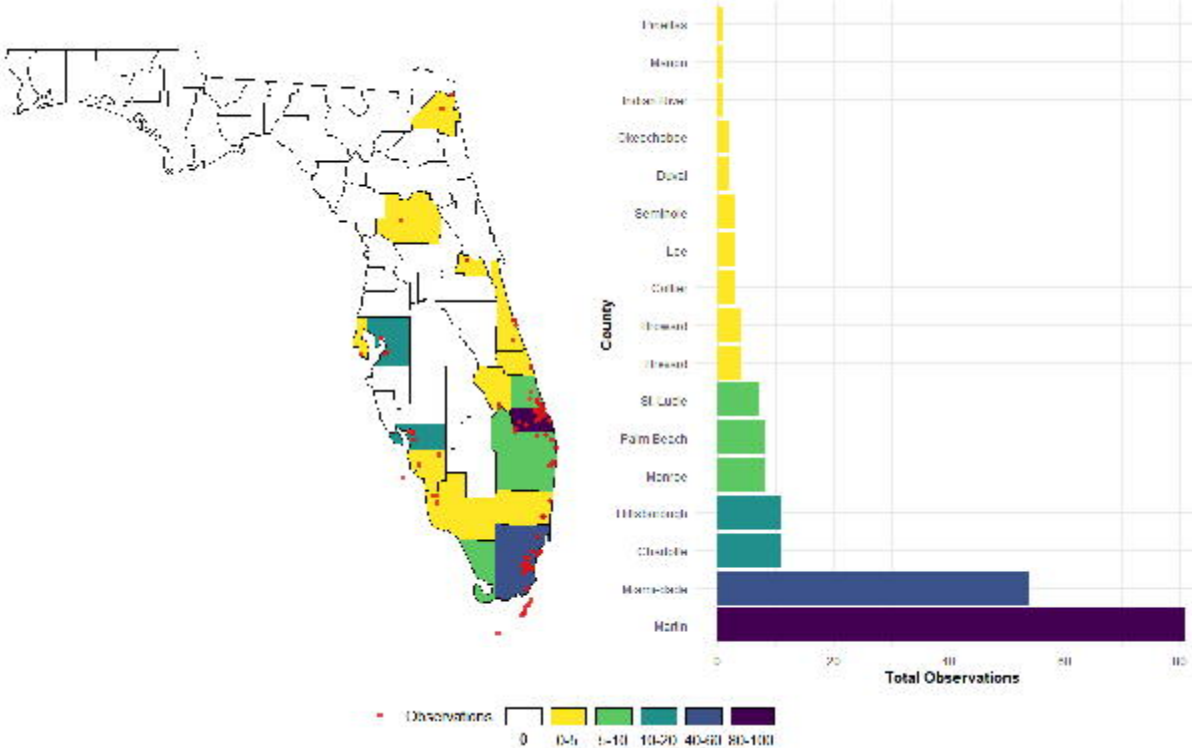


Figure 3. a) Geographic profile origin location output of African red-headed agamas (red crossed circles) in south Florida. Suspected origins (blue) include Coral Castle, and the location of a reptile dealer whose house was destroyed in hurricane Andrew; **b)** modelled origin locations categorized by relevant surroundings, suspect location matches, and labelled points of interest.



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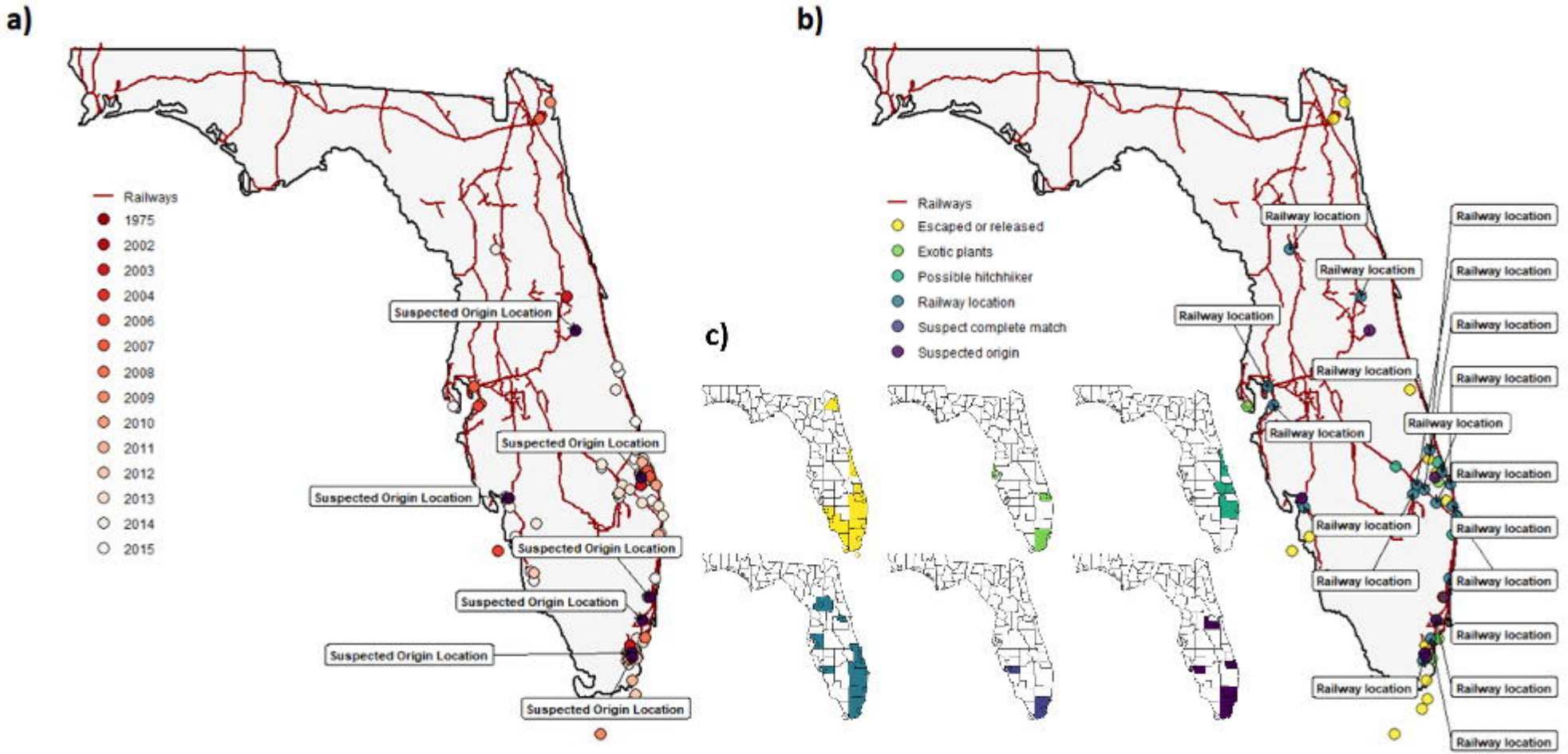
a)
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Escaped or released
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Possible hitchhiker
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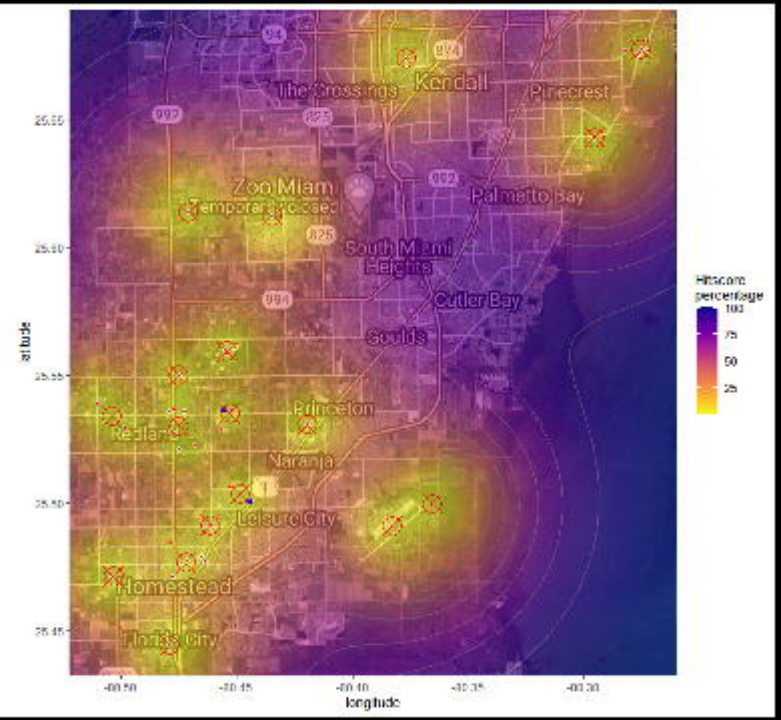
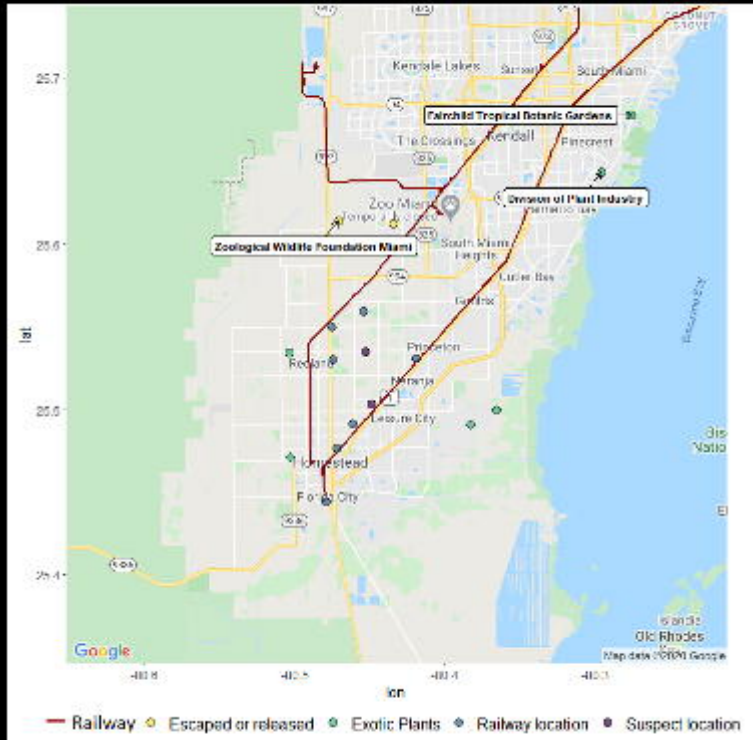
Suspect complete match
Suspected origin
Railway location
c)


The Crossings
Kendall
Pinecrest
Zoo Miami
Temporarily Closed
Palmetto Bay
South Miami Heights
Cutler Bay
Princeton
Redland
Naranja
Leisure City
Homestead
Florida City
Hiscore percentage
100
75
50
25
latitude
longitude


Fairchild Tropical Botanic Gardens
Division of Plant Industry
Zoological Wildlife Foundation Miami
Kendale Lakes
Sunset
South Miami
The Crossings
Kendall
Pinecrest
Zoo Miami
South Miami Heights
Cutler Bay
Princeton
Naranja
Leisure City
Homestead
Florida City
Biscayne Bay
Google
lat
lon
Railway
Escaped or released
Exotic Plants
Railway location
Suspect location