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Hidden in Plain Sight: Detecting Invasive Species When They Are Morphologically Similar to Native Species

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Early detection and rapid response (EDRR) can help mitigate and control invasive species outbreaks early on but its success is dependent on accurate identification of invasive species. We evaluated a novel outbreak in San Diego County, California of the Sonoran Spotted Whiptail (*Aspidoscelis sonorae*) in order to confirm their spread as well as quantify how to better detect and potentially manage this invasive species in California. We found that *A. sonorae* went undetected for over two years due to its morphological similarity to native whiptails and that it has spread rapidly since they were first observed. There are two species of native California whiptails with which *A. sonorae* can be confused locally, the Orange-throated Whiptail (*Aspidoscelis hyperythrus*), and to a lesser extent the Tiger Whiptail (*Aspidoscelis tigris*). We review key diagnostic features to distinguish *A. sonorae* from native California whiptails. We also discuss how to efficiently use widely available community science tools to rapidly assess a novel invasive species outbreak and outline suggestions to help manage cryptic invasive species.

Keywords: Sonoran Spotted Whiptail *(Aspidoscelis sonorae)*, citizen science, community science, iNaturalist, parthenogenesis (asexual reproduction), species occurrence data, diagnostic key, San Diego County

INTRODUCTION

Early detection and rapid response (EDRR) can be critical to controlling, understanding, and stopping the spread of invasive species (Reaser et al., 2020). While there are many methods to detect incipient invasions, community science has seen recent widespread use in helping reduce detection times and mapping the spread of invasive species (Delaney et al., 2008; Gallo and Waitt, 2011; Larson et al., 2020). However, community science approaches can be less effective at certain tasks, such as detecting non-native species when there are similar looking native species (Crall et al., 2011; Aceves-Bueno et al., 2017; Pauly and Gavit, 2019; Pauly et al., 2020) or when the non-natives are difficult to sample or too small to be easily documented through photography (Caley et al., 2020). This can slow detection allowing time for the spread of incipient invasive species. Fortunately, many of these issues can be resolved by increasing awareness amongst community scientists about these difficult-to-identify invasive species. Researchers and community science practitioners can inform potential observers about the diagnostic characters that are useful in the field as well

as characters to include in photo vouchers so others can confirm identifications (Crall et al., 2011; Caley et al., 2020). Here, we report on the introduction and spread of the Sonoran Spotted Whiptail (*Aspidoscelis sonorae* Lowe and Wright, 1964), in San Diego County, California as a case study examining the challenges of rapidly detecting invasive species that look similar to native species. Further, we identify key characters for field identification and photo verification and use this ongoing invasion as an example to highlight strategies that may improve initial detection times for other non-native species.

Much of Southern California resides within the California Floristic Province (CFP), which is one of the Earth's 36 recognized biodiversity hotspots (Mittermeier et al., 2011; Noss et al., 2015). Globally, biodiversity hotspots are at an increased risk for the establishment of invasive reptiles (Li et al., 2016), and this makes detection efforts in these regions a critical conservation priority (Reaser et al., 2020). The CFP is a hotspot because of its remarkable biodiversity and the impacts on it from habitat loss or modification resulting from ranching, agriculture, and/or urban development (Mittermeier et al., 2011). Rapid urbanization within the CFP has given rise to large urban areas (e.g., 18.7 million people in the Greater Los Angeles Area and 3.3 million people in the San Diego-Chula Vista-Carlsbad metropolitan area). Due to the high numbers of people and high volume of goods moving into and throughout urban areas, there are increased chances for the introduction and establishment of non-native species (Spear et al., 2017; Santana Marques et al., 2020). Thus, efforts to improve the early detection of non-natives are especially relevant in and around the major metropolitan areas of the CFP.

Currently, the CFP is home to at least 11 established species of non-native lizards and three species of non-native snakes, most of which are found in urbanized areas (Palmer and Fisher, 2010; Pauly and Borthwick, 2015; Pauly et al., 2015; Reed et al., 2016; Fisher et al., 2020, 2021; Putman et al., 2020). In contrast there are ∼45 species of native lizards and snakes in the CFP, with only a few species occurring in urban areas (Fisher, 2016a,b). Common pathways for the introduction and spread of non-native reptiles include the pet trade, the nursery plant trade, and cargo shipments (Kraus, 2009). In California, plant nurseries can harbor multiple species of invasive reptiles and serve as epicenters of spread (Fisher et al., 2020; Pauly and Fisher, unpubl. data). Generally, invasive reptile species that have successfully invaded and expanded their ranges in Southern California are from similar climates (Mediterranean/desert; e.g., *Aspidoscelis, Hemidactylus, Tarentola*) or have a short time to maturity (e.g., *Anolis, Aspidoscelis, Hemidactylus, Indotyphlops*) as predicted by Van Wilgen and Richardson (2012). Two of these non-native lizards that are spreading in California are parthenogenetic species. These include the Indo-Pacific Gecko (*Hemidactylus garnotii* Duméril and Bibron, 1836; Pauly et al., 2015) and the Sonoran Spotted Whiptail (*Aspidoscelis sonorae*; Winkleman and Backlin, 2016). Parthenogenetic reptiles tend to be quite successful at establishing non-native populations because all that is needed is for a single female individual to be introduced and find conditions suitable for growth and asexual reproduction (Kraus, 2009).

Aspidoscelis sonorae has been present in Orange County in Southern California since at least 2010 (Winkleman and Backlin, 2016; Erickson and Burt, 2019). Within whiptails, *A. sonorae* represents the fifth known species to become introduced (Witmer et al., 2007; Weaver et al., 2011) and is one of the few known diurnal parthenogenetic lizards to become invasive (Kraus, 2009). Additionally, *A. sonorae* is the first non-native lizard in Southern California with native congeneric species present in the state. Field surveys (Fisher and Fisher, unpubl. data) and observations on the iNaturalist community science platform show that *A. sonorae* has been rapidly spreading across Orange County (**Figure 1A**; www.inaturalist.org). This species is native to desert habitats of Arizona, New Mexico, and adjacent Mexico, and seems to do well in the Mediterranean climates of Southern California, especially in urbanized landscapes. However, the current distribution of this species in Southern California is poorly understood due to the difficulty of large scale urban surveys. There are two native whiptail species in Southern California, and both are sexual species—the Tiger Whiptail (*Aspidoscelis tigris* Baird and Girard, 1852) and the Orange-throated Whiptail (*Aspidoscelis hyperythrus* Cope, 1863). Both native species have been declining in Southern California in areas with increasing urbanization (Case and Fisher, 2001; Thomson et al., 2016; Amburgey et al., 2021), and *A. sonorae* might compete with and possibly also consume the native whiptail species leading to further declines. *Aspidoscelis sonorae* is morphologically very similar to the native *A. hyperythrus,* and this makes tracking the spread of the invasive even more challenging. Naturalists and professional biologists assuming a whiptail lizard is an *A. hyperythrus* may not document a non-native species. Additionally, even if a photo voucher is uploaded to a community science platform or deposited in a museum photo collection, the lizard may be incorrectly identified as the more familiar native species.

In Southern California, recent detections of non-native species have resulted from observations by community scientists, especially *via* the iNaturalist platform (e.g., Pauly and Borthwick, 2015; Pauly et al., 2015; Pauly and Gavit, 2019; Fisher et al., 2020, 2021). Efforts by the Natural History Museum of Los Angeles County, the San Diego Natural History Museum, the U. S. Geological Survey, numerous nature centers, and other museums and universities across the region have encouraged high levels of participation in community science platforms such as Herpetological Education and Research Project (H.E.R.P.), HerpMapper, and iNaturalist (Fisher, 2016a). The Reptiles and Amphibians of Southern California (RASCals) project on iNaturalist (for which GBP is the lead scientist) has further accelerated the documentation of reptiles and amphibians (Spear et al., 2017) as has the San Diego Invasive Species Watch on iNaturalist (Richmond et al., in prep.). Thus, there is a large community of passionate naturalists and community scientists that are already helping to reduce detection times for potential invasive species. Despite these efforts, documenting the introduction and spread of *A. sonorae* in Southern California has proven especially challenging relative to the other non-native lizards introduced to California. This is mainly because they are difficult to differentiate from the native *A. hyperythrus*. Further

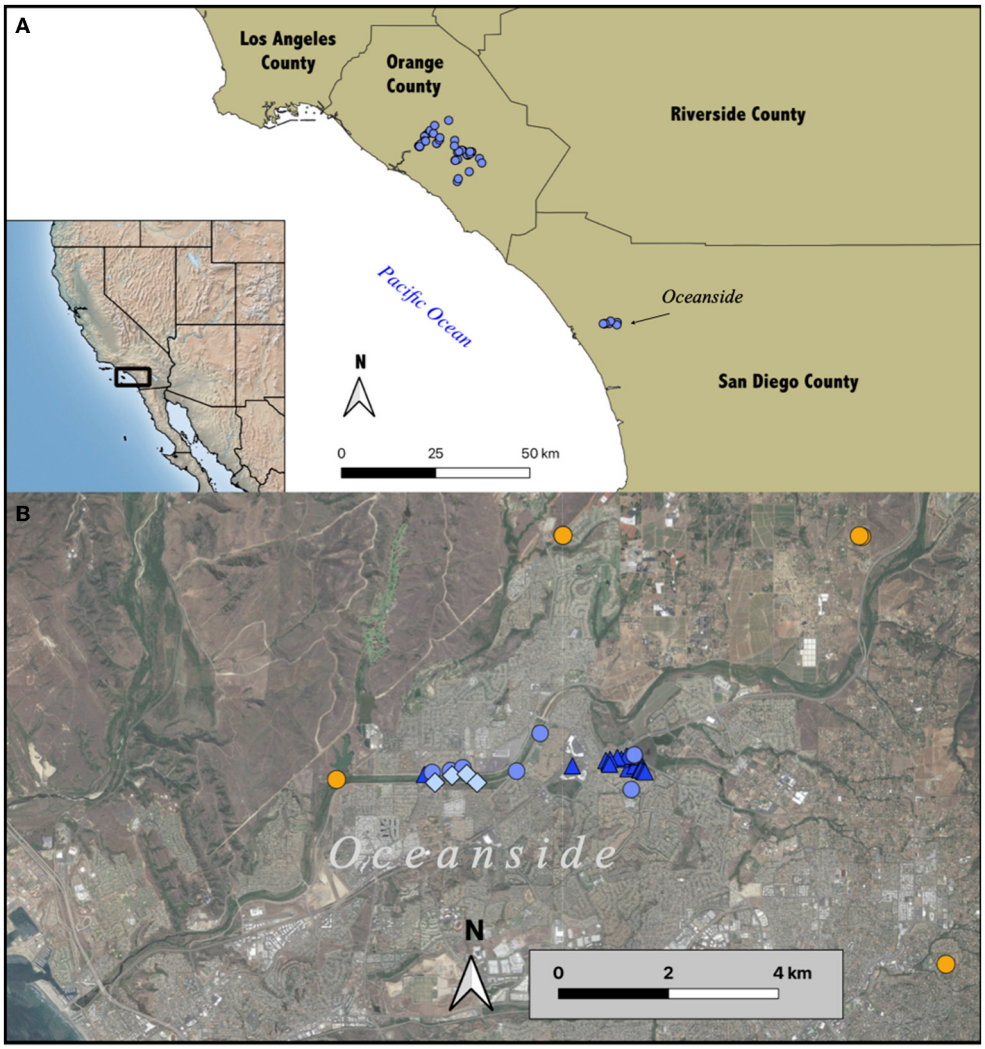

FIGURE 1 | Distribution of *Aspidoscelis sonorae* in Southern California. **(A)** Confirmed *A. sonorae* in Orange and San Diego counties based on research-grade iNaturalist observations. **(B)** The distribution of the invasive *A. sonorae* (medium blue circles for iNaturalist observations; dark blue triangles for field observations by authors), probable *A. sonorae* based upon iNaturalist observations that cannot be confidently identified to species (pale blue diamonds), and native Orange-throated Whiptails (*A. hyperythrus*; orange circles).

compounding this issue, lizards in the genus *Aspidoscelis* are fast moving, active foragers which makes getting high quality photographs to post on community science platforms especially problematic. Even with high quality pictures, it can be difficult to accurately distinguish between these two species. This lack of diagnosability leads to an inaccurate tracking of the spread of *A. sonorae* at the edges of known localities, prevents new localities from being easily found, and can confound the true range of the native species because the invasive species can occupy suboptimal native habitat.

Here we use an incipient invasion of *A. sonorae* as an example to show how misidentifications can be reduced when dealing with morphologically similar species using community science. This study is motivated by the photo-documentation of *A. sonorae* more than 50 km south of the nearest known *A. sonorae* in Orange County by iNaturalist user J. Fishinger in August, 2020 (iNaturalist 55755922; originally identified only as *Aspidoscelis* and then identified within a few days as *A. sonorae* by GBP and others). This observation triggered examination of other iNaturalist observations, which revealed that the species had been photographed 3.3 km west of iNaturalist 55755922 26 months earlier but misidentified as the native *A. hyperythrus* (iNaturalist 13276378). We review key morphological characteristics necessary to reduce misidentifications, provide suggestions for characters to include in photographs, and document this species expansion into San Diego County for the first time. We conclude with suggestions for other researchers, invasive species' biologists, and community

science practitioners who hope to use community science to reduce detection times of non-native species.

MATERIALS AND METHODS

Species Background

In Southern California there are two native species of whiptail lizards, the Orange-throated Whiptail (*Aspidoscelis hyperythrus*) and the Tiger Whiptail (*Aspidoscelis tigris*), which have recently been evaluated as to their conservation status (Thomson et al., 2016). Additionally, the Sonoran Spotted Whiptail (*Aspidoscelis sonorae*) has been introduced into this region and is known from Orange County, California (Winkleman and Backlin, 2016; Erickson and Burt, 2019). Within California, the invasive spotted whiptails were classified as part of the *Aspidoscelis flagellicauda/sonorae* complex because available morphological variation and mtDNA sequence data were insufficient to identify the exact species. However, since Taylor et al. (2018) synonymized *A. flagellicauda* with *A. sonorae,* the invasive species in California is now referred as *A. sonorae.* This species is native to Arizona, New Mexico, and northern Mexico occurring in higher elevation montane desert habitat (Taylor et al., 2018).

Within California, the native *Aspidoscelis hyperythrus* has a small distribution from southwestern San Bernardino County and Orange County southward through western Riverside County and San Diego County (Ver Hoef et al., 2001; Stebbins, 2003). Its range extends southward through most of the Baja California Peninsula. Previously *A. hyperythrus* was listed as a Species of Special Concern within California (Thomson et al., 2016) but is now on the California Department of Fish and Wildlife watch list (California Natural Diversity Database, 2022). Of the two native whiptail species, *A. hyperythrus* is more likely to be confused with the invasive *A. sonorae. Aspidoscelis tigris*, the other native whiptail, is a wide ranging species that is composed of multiple subspecies; three subspecies reside in California (Stebbins, 2003). The species occurs widely across coastal habitats but is also found inland, through the mountains, and into and across the desert reaches of California (Stebbins, 2003). *Aspidoscelis tigris* occurs widely across the western United States and northeastern Mexico. It is larger than *A. hyperythrus* and has been declining in parts of its range due to urbanization (Thomson et al., 2016). This species is less likely to be confused with the invasive *A. sonorae*.

Database Surveys

To look for new records of *Aspidoscelis sonorae* in San Diego, we examined various community science platforms including the Herpetological Education and Research Project (H.E.R.P.; www.naherp.com), HerpMapper—Global Herp Atlas (www.herpmapper.org), and iNaturalist (www.inaturalist.org). The first two platforms are typically used by skilled identifiers who list the identification as they enter the record; there is little option for the community to confirm species identifications on these platforms, though others can comment on identifications, and as needed, they can be updated. The iNaturalist platform is used by these higher skilled identifiers as well as those with less taxonomic expertise. The original observer may or may not identify an organism to species, but the iNaturalist community can easily contribute identifications leading to a community-supported identification. Because of these differences, we searched these platforms differently. For H.E.R.P. and HerpMapper, we simply checked for San Diego County observations of *A. sonorae*. For iNaturalist, to find observations of *A. sonorae* within San Diego County, we looked at all whiptail (*Aspidoscelis*) occurrences. Occurrences were searched until the date of June 1, 2021 for H.E.R.P. and HerpMapper and through October 31, 2021 for iNaturalist. *Aspidoscelis sonorae* has mainly been misidentified as *A. hyperythrus* so we especially scrutinized records of *A. hyperythrus* in order to find pictures with potentially misidentified *A. sonorae.* Some individuals could not be positively identified to species level due to the quality of photographs, and were identified only to the genus *Aspidoscelis.*

Field Surveys

Field surveys targeted the two locations in Oceanside, San Diego County, where we identified *A. sonorae* from iNaturalist observations (iNaturalist 55755922 and 13276378). These two locations are on opposite sides of the San Luis Rey River and could represent population expansion following a single introduction or separate introduction events. For sampling, we treated these records as separate sites, and conducted surveys on foot between 10 am and 5 pm. We conducted surveys on 15 August 2020, 27 August 2020, 12 October 2020, and 2 June 2021. We surveyed in the immediate area of the two original iNaturalist locations to determine range boundaries and then surveyed points of interest between these two initial sites to determine whether this was one connected population. Sampling of intermediate sites was also done because lizards of the genus *Aspidoscelis* have large home range sizes >500 m (Eifler and Eifler, 1998), which can make detecting individuals more difficult. We conducted surveys primarily from sidewalks as most habitat is private property (house lots) and inaccessible to us.

Morphological Characters

We followed Taylor et al. (2018) for guidance on diagnosing invasive *Aspidoscelis sonorae* within Southern California. We used museum specimens of *A. hyperythrus* and *A. tigris* to look for diagnosable differences between the species that could be seen on photos. We also referred to Burt (1931; also Wright and Lowe, 1967) to identify characters useful for distinguishing between species groups within *Aspidoscelis*. We looked at snout vent length (SVL) for the three species to ascertain any size differences that might supplement other characters in a useful diagnostic key. For the two native species, we used previously collected measurements from the USGS Pit-fall trap studies across Southern California (Case and Fisher, 2001; Fisher et al., 2008; Fisher, 2016b; Amburgey et al., 2021). Using these data, we defined SVL for adults as >80 mm for *A. tigris* (Goldberg, 1976) and >50 mm for *A. hyperythrus* (Bostic, 1966). For the invasive *A. sonorae,* we used measurements for some of the pattern classes presented in Taylor et al. (2018); these authors only measured the largest individuals available (all above 77 mm SVL), allowing us to compare the maximum sizes across groups but not to compare

TABLE 1 | iNaturalist observations that are confirmed or possible invasive *Aspidoscelis sonorae* in northwestern San Diego County.

Observation No.	Species	Date*	Locality**	Observer***	Identification history
13276378	*Aspidoscelis sonorae*	6/9/18	Available	D. R. Sozzani (deborah20)	Research grade as *A. hyperythrus* before being correctly identified by our team as *A. sonorae*
55755922	*Aspidoscelis sonorae*	8/5/20	Available	J. Fishinger (jjfish)	Identified by observer only to genus and then by our team as *A. sonorae*
58354052	*Aspidoscelis sonorae*	9/1/20	Available	J. Fishinger (jjfish)	Identified correctly as *A. sonorae*
75232275	*Aspidoscelis sonorae*	4/25/21	Available	D. R. Sozzani (deborah20)	Identified correctly as *A. sonorae*
78404592	*Aspidoscelis sonorae*	5/11/21	Available	J. Dabbert (chiiave)	Identified by observer as *A. hyperythrus* and then correctly identified by our team as *A. sonorae*
80545340	*Aspidoscelis sonorae*	5/27/21	Available	B. Perkins	Identified correctly as *A. sonorae*
81581452	*Aspidoscelis sonorae*	6/??/21	Not available	(bttiger)	Research grade as *A. hyperythrus* before being correctly identified by our team as *A. sonorae*
84300160	*Aspidoscelis sonorae*	6/23/21	Available	D. L. Bowls (dlbowls)	Identified correctly as *A. sonorae*
87635967	*Aspidoscelis sonorae*	7/18/21	Available	(frmins)	Identified by observer only to genus and then by our team as *A. sonorae*
90301782	*Aspidoscelis sonorae*	8/7/21	Available	D. R. Sozzani (deborah20)	Identified by observer only to genus and then by our team as *A. sonorae*
13275964	*Aspidoscelis sp.*	6/9/18	Obscured	D. R. Sozzani (deborah20)	Cannot be confidently identified to species
42180699	*Aspidoscelis sp.*	4/13/20	Obscured	(nsd)	Cannot be confidently identified to species
78412234	*Aspidoscelis sp.*	5/11/21	Obscured	J. Dabbert (chiiave)	Cannot be confidently identified to species
78412483	*Aspidoscelis sp.*	5/11/21	Available	J. Dabbert (chiiave)	Cannot be confidently identified to species

*For some records, the day of the month was missing from the database.

**Available means that the date and locality data were available on iNaturalist "Obscured" means data were available to GBP as the lead scientist for the RASCals project or obtained by contacting the observer. "Not available" means that the data were obscured and the observer did not respond to inquiries.

***Observer names are given as name (iNaturalist username) when possible.

adult size distributions. We used R package software to show body size versus species/pattern class.

RESULTS

Database Surveys

We found no records for *A. sonorae* in either H.E.R.P. or HerpMapper for San Diego County. Within the iNaturalist platform, research-grade means that the observation has a photo, locality and date data, and a community supported identification. For San Diego County we found 10 observations of *A. sonorae* and four observations of whiptails that could not be confidently identified to species due to photo quality and/or key characters not being visible (**Table 1**). Of the 10 *A. sonorae* observations, three had been misidentified as *Aspidoscelis hyperythrus*, including iNaturalist 13276378 which was observed 7/9/2018 and achieved research-grade status as *A. hyperythrus* before being correctly identified 26 months later as *A. sonorae.* This represents the earliest known record of this invasive species in San Diego County. Thus, in this case, this was a misidentification. Similarly, iNaturalist 81581452 achieved research grade status as *A. hyperythrus* before being identified by us as *A. sonorae,* and iNaturalist 78404592 was also initially misidentified as *A. hyperythrus* (**Table 1**). With increasing awareness of the presence of *A. sonorae* in the Oceanside area of San Diego County, other observations were correctly identified as *A. sonorae* (iNaturalist 58354052, 75232275, and 84300160) or were identified by the initial observer only to genus and then by us as *A. sonorae* (iNaturalist 87635967, 90301782).

Field Surveys

During our August 2020 and June 2021 surveys, over 150 *A. sonorae* of all size classes were seen across the sites, suggesting a reproductive and expanding population. Only a single *A. sonorae,* a juvenile, was seen during the October 2020 survey. One juvenile was collected on 8/13/20 (LACM RNF), three additional specimens (one adult, one juvenile, one hatchling) were collected on 8/26/20 (LACM 194168–194170), and three additional adults were collected on 6/2/2021. There is a total distance of 4.02 km between the two farthest individuals detected. In our surveys, the lizards were not continuous across the 4-km survey area, but were concentrated on each end in the vicinity of the two original iNaturalist observations, and at an urban shopping center in the middle (**Figure 1**). However, community scientists have made several additional observations along the San Luis Rey River in this intervening area (**Table 1**; iNaturalist 80545340, 84300160). During the surveys, native *Sceloporus occidentalis* (Baird and Girard, 1852) and *Uta stansburiana* (Baird and Girard, 1852) were observed sympatrically with *A. sonorae.* No other species of *Aspidoscelis* were detected during the surveys (**Figure 1**).

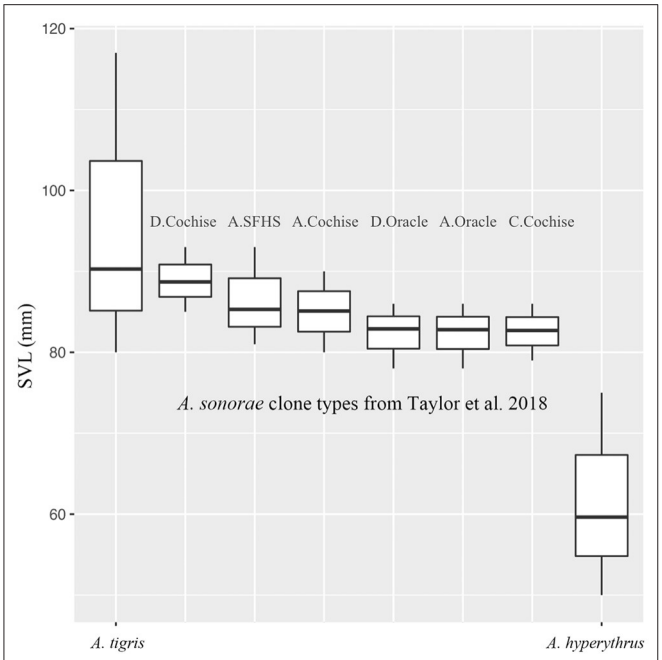

FIGURE 2 | Body size (snout to vent length [SVL] in mm) for native species of *Aspidoscelis* from Southern California and pattern classes for *Aspidoscelis sonorae* (Taylor et al., 2018). Note that Taylor et al. (2018) only examined the largest adults in their populations (those over 77 mm SVL); thus, comparisons should only be made across maximum sizes of each group. *Aspidoscelis sonorae* from Taylor et al. (2018) are listed as the pattern class (A, C, or D) and then the location (Cochise, SFHS, or Oracle).

Morphological Differences

We show the size differences (SVL) between the native species of whiptails in coastal Southern California compared with the native range of *A. sonorae* (**Figure 2**). The largest adult *A. sonorae* average between 83 and 89 mm depending on clone type with a maximum size of 93 mm from a total of 72 specimens (Taylor et al., 2018). This is larger than *A. hyperythrus* which has a maximum size of 75 mm measured from a total of 11,476 specimens. The *A. tigris* we documented had a maximum size of 117 mm measured from 1,910 specimens from coastal Southern California. Thus, adult *A. sonorae* and *A. tigris* overlap in body size, but *A. tigris* reaches a maximum length almost 25 mm longer than *A. sonorae*.

In addition to body size, a number of other morphological characteristics are useful in differentiating invasive *A. sonorae* from the two native whiptails (**Table 2**). There are four fairly easily differentiable characteristics between *A. sonorae* and *A. hyperythrus*: (1) young individuals of *A. hyperythrus* have a blue tail whereas *A. sonorae* have a slight orange or red coloration to the tail or the tail is slightly lighter but similar to the body coloration; (2) *A. hyperythrus* develops orange coloration under their throat and body as they mature; (3) *A. hyperythrus* (at least in Southern California) have paravertebral stripes which merge at the base of the tail or more anteriorly in the pelvic region becoming a single vertebral stripe that continues onto the tail, whereas *A. sonorae* have paravertebral stripes that remain parallel through the pelvic region and then fade on the upper tail; and (4) *A. hyperythrus* have an undivided frontoparietal scale; they sometimes have only three supraocular scales; and they sometimes have circumorbital scales that extend forward of the frontal-frontoparietal plate divide [**Figure 3**; note that Stebbins (2003) refers to these circumorbital scales as the supraorbital semicircle]. *Aspidoscelis sonorae* has a divided frontoparietal scale and three or four supraocular scales, and circumorbital scales which end at or posterior to the frontal and frontoparietal plate divide. *Aspidoscelis tigris* does not generally have much striping, as its pattern tends to be mottled; therefore, it is much easier to tell apart from both *A. hyperythrus* and *A. sonorae*. The head scales of *A. tigris* are similar to those of *A. sonorae* in that they have a divided frontoparietal plate, circumorbital scales which end at or posterior to the frontal and frontoparietal plate divide, and four supraocular scales.

In reviewing iNaturalist observations of whiptails from across Southern California, at least three (A, C, D) of the *A. sonorae* pattern classes recognized in Taylor et al. (2018) are present in Southern California. However, we only observed pattern classes A and C in San Diego County, per the definitions of Taylor et al. (2018).

DISCUSSION

Sonoran Spotted Whiptails in Southern California

This study documents the first known record of *Aspidoscelis sonorae* in San Diego County, and shows that this species is continuing to spread in Southern California. We found evidence for a spreading and reproductive population center that remained undetected for at least 2 years. The nearest known population of invasive *A. sonorae* is ∼50 km away, suggesting either that this species was moved 50 km by humans or that there are other pathways by which the species is repeatedly introduced to California. Care should be taken to understand these pathways and potentially close them, especially if this species proves to affect native species. Multiple individuals were found on both sides of the San Luis Rey River, which has been shown to be a biogeographical break for certain species (Vandergast et al., 2008). As such we are not able to assess if the *A. sonorae* are all from the same founding event. Urbanization can cause biogeographical barriers to weaken, so this could be one continuous population. Because *A. sonorae* is parthenogenetic, it is also possible they have only crossed the river once and are spreading as one invasion but in disjunct suitable habitats. While this river may have once inhibited some native species from crossing, it remains to be seen if invasive species will have that same issue. Alternatively, there could be two separate introduction events to Oceanside, each giving rise to the areas of denser observations on the west and east end of our survey area, with individuals slowly spreading into the intervening region where there are fewer observations at present. Molecular analyses are currently in progress with individuals from across the Oceanside area and other parts of California to assess the

TABLE 2 | Diagnostic characteristics to distinguish between the two native species of whiptail and the invasive Sonoran Spotted Whiptail (bold) in Southern California.

Character	*A. hyperythrus*	*A. sonorae*	*A. tigris*
Size (**Figure 2**)	Small; <75 mm as adult	Medium	Large
Tail as juvenile	Blue	Slightly reddish to similar coloration to body	Blue/green
Underside as adult	Orange	White	White
Complete straight striping as juvenile	Yes	Yes	Wavy stripes and sides not completely striped
Striping as adults	Yes	Yes	No; mottled pattern
Paravertebral stripes	Merge posteriorly, generally in the area of the hind limbs, forming a single vertebral stripe on the tail	Stripes are parallel through pelvic region and fade on the upper tail	Fade or become irregular abruptly as enter tail
Frontoparietal plate	Not divided	Divided	Divided
Supraoculars	3 or 4	4	4
Circumorbital scales extend anteriorly past frontal-frontoparietal suture – creating a semicircle around the supraoculars (**Figure 3**)	Sometimes	No	No

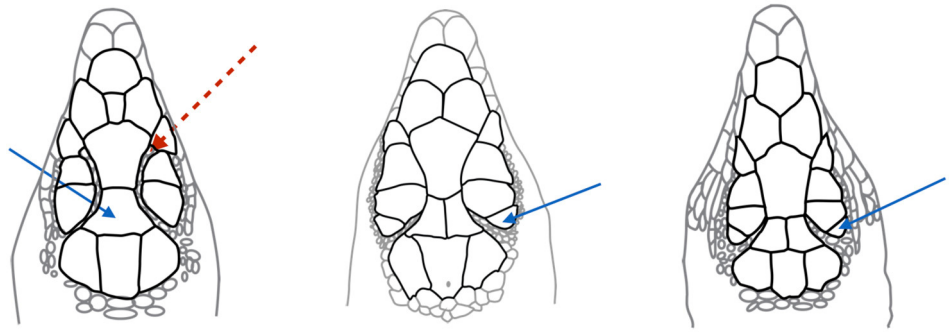

FIGURE 3 | Left is a head drawing of *Aspidoscelis hyperythrus*, middle is *A. sonorae*, and right is *A. tigris*. Blue arrow on left shows the non-divided frontoparietal that is diagnostic of *A. hyperythrus*. Blue arrows on middle and right drawings show additional supraocular scale that is sometimes absent from *A. hyperythrus*. The circumorbital scales are the small scales between the supraocular scales and the frontoparietal scale. Only in *A. hyperythrus* do the circumorbital scales sometimes extend forward of the frontal-frontoparietal suture (dashed red arrow in left panel).

number of independent introduction events and to help identify the geographic region of the source population(s).

In Oceanside, the invasive *A. sonorae* co-occur with at least three native lizards, the Side-blotched Lizard (*U. stansburiana*), the Western Fence Lizard (*S. occidentalis*), and the Southern Alligator Lizard (*Elgaria multicarinata* Blainville, 1835). We observed the first two during our surveys but not the more secretive *E. multicarinata,* which has been documented by others in the area (iNaturalist 10220595, 15585294, and 50495145). These three species are also found in and around *A. sonorae* in Orange County. While *A. sonorae* is currently found in urban parts of Oceanside where there are no known native whiptail lizards, both native species of whiptail are not far from the expanding range of this population. In Orange County, the native and invasive whiptails are overlapping or in proximity to each other. Further work is needed to establish any impacts that *A. sonorae* may have on the native species of lizards and other potential competitors and prey species.

An additional threat presented by *A. sonorae* is potential hybridization with the native whiptails. Sonoran Spotted Whiptails are known to hybridize with *A. tigris* in their native range (Lowe et al., 1970). It is currently unknown whether *A. sonorae* can hybridize with the native *A. hyperythrus*. In areas where there are already reduced numbers of native whiptails (e.g., urban areas; Case and Fisher, 2001), the native sexual species could be negatively impacted if hybridization between these species frequently occurs. Additional molecular studies with increased sampling within and around the introduced populations will be especially helpful if hybridization events with native *Aspidoscelis* occur.

The establishment and rapid spread of *A. sonorae* in Southern California is somewhat unexpected given the level of relatedness and phenotypic similarity (i.e., same genus) to native whiptails

(Van Wilgen and Richardson, 2012). Currently *A. sonorae* is only found in urbanized areas where the native species have been displaced (Case and Fisher, 2001). It is possible that *A. sonorae* will not be able to invade more natural habitats where it will be excluded by native sexual species as described in the weed hypothesis (Wright and Lowe, 1968), which suggests that parthenogenetic whiptail species tend to be found in marginal or disturbed habitats or in ecotones. Here again, iNaturalist observations have an important potential role as these recent species occurrence records can be used for ecological modeling studies to understand habitat use by the native and invasive whiptails.

Differentiating Native and Non-native Whiptails in California

Community science tools like iNaturalist are useful for identifying and detecting invasive species, although there are challenges in detecting non-native species that are extremely similar morphologically to co-occurring native species or that cannot be easily photographed. Documentation of *Aspidoscelis sonorae* is hampered for both of these reasons—it looks similar to native species and it is also fast and only seasonally-active (Routman and Hulse, 1984), making obtaining high quality photos a challenge during the warmer months when the species is most active. By creating a diagnostic key, we hope to inform community science users and land managers about how to distinguish between *A. sonorae* and the native whiptails (see also **Supplemental Figure 1**). In the Results and in **Table 2**, we list characters that are useful in differentiating the invasive *A. sonorae* from the native *A. hyperythrus* and *A. tigris*. The scale characters (final three characters in **Table 2**) are useful once an animal or preserved specimen is in hand, but these characters are unlikely to be useful when someone is only taking a photograph. For community scientists taking photographs that others will scrutinize to confirm species identification, it is especially helpful to photograph the tails of juveniles, the throat and ventral region of adults, and the dorsal striping especially near the hind limbs and base of the tail. Photographs showing these characters should allow correct identification of adults and juveniles.

Suggestions for Detecting Cryptic Invasive Species *via* Community Science

Community science efforts, and especially iNaturalist, can be useful in decreasing detection times for novel invasive species and for tracking the spread of ongoing invasions. However, for species that are morphologically similar to co-occurring native species, are temporally or climatically limited in their activity periods, or are otherwise difficult to photograph, invasive species biologists and community science practitioners can take additional steps to increase the likelihood that new records are documented and correctly identified. Based on our experiences working with community scientists in detecting *A. sonorae* and other non-native species in California, we provide the following suggestions:

1. Identify diagnostic characters that can be used to differentiate native and non-native species when the specimen is in hand, and especially when it is at a slight distance and is only being photographed.
2. Increase awareness among biologists, landscape managers, and especially community scientists about the potential non-native species, similar-looking native species, key characters for differentiating native and non-native species, and key characters to include in voucher photographs to assist in subsequent identifications. Share this information broadly, such as through social media, traditional media, communications to colleagues, journal entries on iNaturalist projects, and directly with iNaturalist users through personal messages and comments on relevant observations.
3. Biologists and community science practitioners concerned about potential invasive species could actively monitor relevant community science platforms for observations correctly identified as a non-native species and, perhaps more importantly, for observations of non-native species that are misidentified as a native species. Active community scientists can also be encouraged to do the same.
4. For species that are especially difficult to document, invasive species biologists likely cannot rely solely on photo-vouchering through community science to reduce detection times. Instead, they can use additional trapping and monitoring efforts including potentially partnering with community members to set up monitoring stations on private property otherwise inaccessible to the biologists.

In our study of *A. sonorae,* we have used many of the approaches above. Following the 2020 observation of this species in Oceanside, we scrutinized hundreds of whiptail observations in San Diego and Orange counties, routinely commenting on observations and sending personal messages to observers. Subsequent observations posted to iNaturalist were typically uploaded with identifications only to genus (i.e., *Aspidoscelis*) when the observer could not confidently differentiate between the native and non-native species or as *A. sonorae* when the observer was able to correctly identify the invasive species.

Longer-term, another way to improve the detection of cryptic invasive species in community-science generated photographs is to use machine-learning algorithms trained to detect the species of interest (Wäldchen and Mäder, 2018; Weinstein, 2018). At present, iNaturalist uses machine-learning algorithms for automated species/taxon identification. The algorithm is trained on an existing set of research-grade observations. Modifications to this algorithm or separate algorithms dedicated to particular taxa or identification challenges could automate the review of new observations, "flagging" records of suspected non-natives that can then be scrutinized by experts. Not only is accurate recognition and identification of species important for tracking the spread of *A. sonorae* within California, it is also important for researchers who may be using inaccurate occurrence data, e.g., data with multiple species under the umbrella of only one species.

CONCLUSION

We found that *Aspidoscelis sonorae* is present and reproducing within San Diego County. We suggest that photographing the

throat and ventral region of adults, the dorsal region of the head, dorsal striping especially near the hind limbs and base of the tail, and the tails of juveniles can assist with identifications from photos. Focusing on these key characters to increase accuracy of identifications could also improve tracking the spread of this invasive species. To this end, we have created a diagnostic key to help land managers and community scientists to properly identify and photograph these lizards (**Table 2**; **Figure 3** and **Supplemental Figure 1**). Currently within Southern California, there may be more unknown populations of *A. sonorae*, hidden in plain sight.

DATA AVAILABILITY STATEMENT

Data are available *via* iNaturalist and from the corresponding authors and/or collections staff, Department of Herpetology, Natural History Museum of Los Angeles County.

ETHICS STATEMENT

The animal study was reviewed and approved by UC Davis ACUC.

AUTHOR CONTRIBUTIONS

SF, RF, and GP contributed to writing, design, and implementation of the study. All authors contributed to the article and approved the submitted version.

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SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fcosc.2022.846431/full#supplementary-material

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