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Authors: Pfeiler, Edward, Johnson, Sarah, and Markow, Therese A.

Source: The Journal of the Lepidopterists' Society, 66(4) : 185-198

Published By: The Lepidopterists' Society

URL: https://doi.org/10.18473/lepi.v66i4.a1

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Journal of
The Lepidopterists' Society

Volume 66 2012 Number 4

*Journal of the Lepidopterists' Society*
66(4), 2012, 185–198

# DNA BARCODES AND INSIGHTS INTO THE RELATIONSHIPS AND SYSTEMATICS OF BUCKEYE BUTTERFLIES (NYMPHALIDAE: NYMPHALINAE: *JUNONIA*) FROM THE AMERICAS

Edward Pfeiler,

Centro de Investigación en Alimentación y Desarrollo, A.C., Unidad Guaymas, Apartado Postal 284, Guaymas, Sonora C.P. 85480, México; email: pfeiler@ciad.mx

Sarah Johnson,

Division of Biological Sciences, University of California, San Diego, La Jolla, California 92093

and

Therese A. Markow

Division of Biological Sciences, University of California, San Diego, La Jolla, California 92093

**ABSTRACT.** Nucleotide sequence data from a segment of the mitochondrial cytochrome c oxidase subunit I (COI) gene, known as the barcode segment, were used to examine phylogenetic relationships and systematics of buckeye butterflies (Nymphalidae: Nymphalinae: *Junonia*) from the New World, with emphasis on taxa from western North America. Three nominal species have been recognized for North America, *J. evarete* (Cramer), *J. genoveva* (Cramer), and *J. coenia* Hübner, with additional species recently proposed for the West Indies and northern South America. The distinctive Andean buckeye, *J. vestina* C. Felder & R. Felder, along with *J. evarete* and *J. genoveva*, are also components of the South American fauna. With the exception of *J. vestina*, butterflies comprising the New World *Junonia* have had a confused taxonomic history, and species assignments are often problematic. Our results show that the barcode segment resolves the two major clades of New World *Junonia*, referred to here as clades A and B, with similar high support seen in an earlier phylogenetic study using both mitochondrial and nuclear genes. Within clade A, *J. vestina* resolved in a basal position to *J. evarete* from South America and the Caribbean. The data further suggest that species assignments in some populations of New World *Junonia* clustering in clade B (*J. coenia* + *J. genoveva*) need to be reevaluated. DNA barcodes, although failing to resolve all recognized species and subspecies level taxa of New World *Junonia*, probably owing to relatively recent divergences, can provide valuable tools for identifying the two major lineages, and when used in conjunction with morphological, ecological, behavioral and life history information can provide insights into the taxonomy and evolution of this difficult group.

**Additional key words:** cytochrome c oxidase subunit I, dispersal, genetic distance, population structure, speciation.

Butterflies commonly known as buckeyes (Nymphalidae: Nymphalinae: *Junonia*) are widely distributed in the Americas, being found from southern Canada to South America. In an early treatment of the genus, Forbes (1928) recognized two species of *Junonia* in the New World, *J. vestina* C. Felder & R. Felder, a high altitude form found throughout the Andes of South America (Fig. 1), and *J. lavinia* (Cramer) [= *J. evarete* (Cramer)] in which he grouped all others forms that were morphologically similar and distinct from *J. vestina*. In the present paper we refer to buckeyes included in *J. lavinia* as the *J. evarete* complex [*Junonia lavinia* is now recognized as a permanently invalid synonym of *J. evarete* (Comstock 1942)]. The genus *Precis* also has been used for the New World buckeyes, but butterflies belonging to this genus are now known to be restricted to Africa (Wahlberg et al. 2005). Recently, Pelham (2008) recognized three nominal species of *Junonia* belonging to the *J. evarete* complex as defined here: *J. evarete* (Cramer), *J. genoveva* (Cramer) and *J. coenia* Hübner, as well as three subspecies: *J. evarete nigrosuffusa* W. Barnes & McDunnough, *J. evarete zonalis* C. Felder & R. Felder and *J. coenia grisea* Austin & J. Emmel. In addition, ongoing taxonomic studies on *Junonia* from the West Indies and northern South America suggest that additional species level taxa

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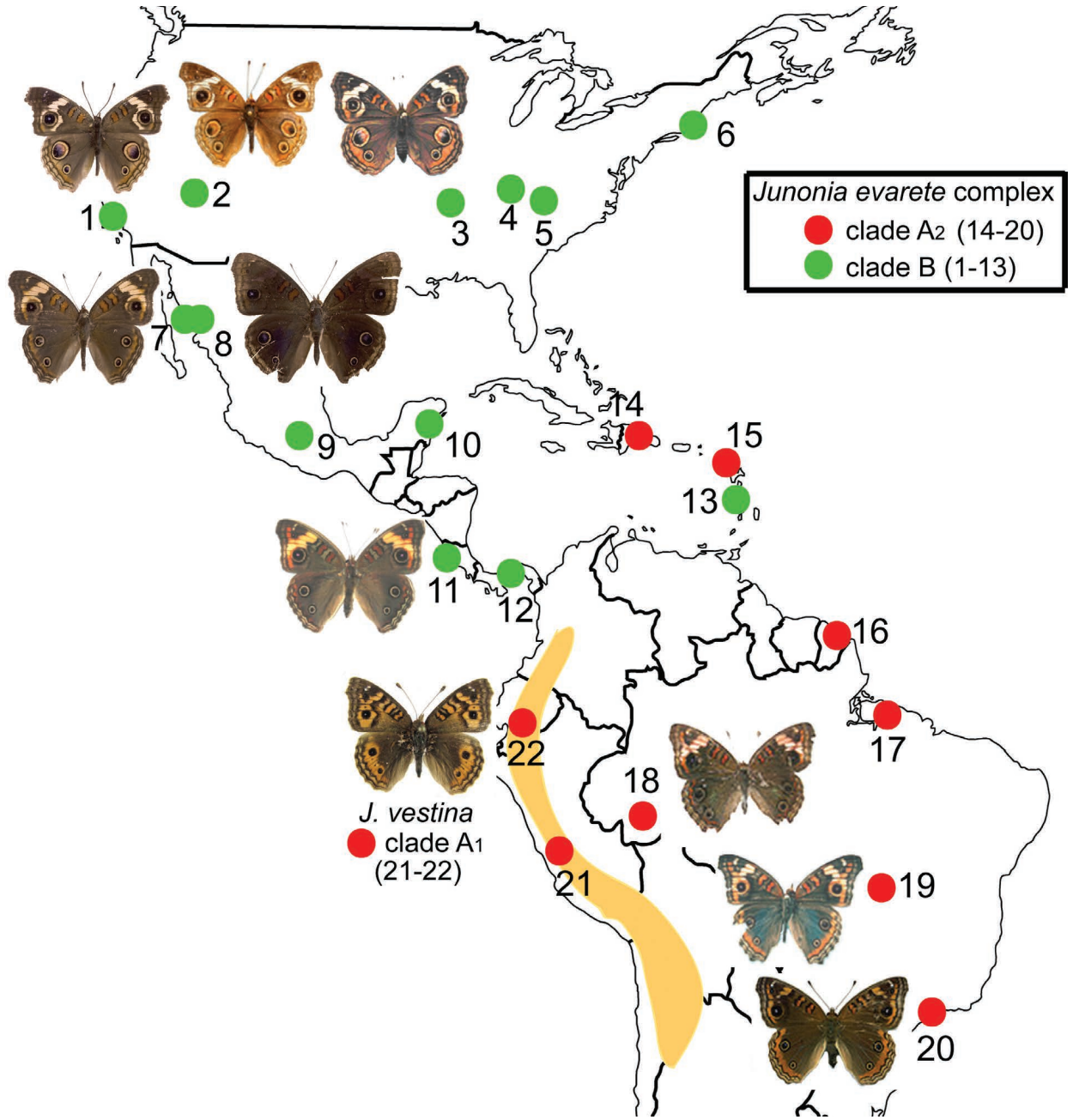



FIG. 1. Map of North and South America showing collection localities and phenotypic variability of *Junonia* spp. at selected localities where dorsal images were available. Red and green dots correspond to the two main clades (A and B, respectively) of New World *Junonia* (see Fig. 2). The shaded area represents the approximate geographic distribution of the Andean buckeye, *J. vestina*. Voucher codes for each species are given below (see Table 1 for details). Scientific names in parentheses are suggested changes in assignment based on data presented here (see Discussion regarding the assignment of *J. nigrosuffusa*) or unpublished data (C. Brévignon, pers. com.). **1,** *J. coenia grisea* (CIAD 10–B03); **2,** *J. coenia coenia* (NW38–18); **3,** *J. coenia coenia* (female) (NW85–13); **4,** *J. coenia coenia* (no image) (Bio175–17); **5,** *J. coenia coenia* (no image) (DNA–ATBI–0802 and –0816); **6,** *J. coenia coenia* (no image) (TDWG–0126); **7,** *J. evarete* (= *J. genoveva*; CIAD 10–B19; Estero del Soldado); **8,** *J. evarete nigrosuffusa* (= *J. nigrosuffusa*; CIAD 10–B24); **9,** *J. evarete* (no image) (= *J. genoveva*; JM6–10); **10,** *J. evarete* (no image) (= *J. genoveva*; MAL–02877); **11,** *J. evarete* (= *J. genoveva*; 05–SRNP–58293); **12,** *J. evarete* (no image) (= *J. genoveva*; YB–BCI12765); **13,** *J. genoveva* (no image) (= *J. neildi* Brévignon [C. Brévignon, pers com.]; NW136–16); **14,** *Junonia* sp. (no image) (= *J. evarete*; NW153–12); **15,** *J. evarete* (no image) (NW136–17); **16,** *Junonia* spp. (no images) (UK4–14, –15, –16); **17,** *J. evarete* (no image) (NW151–3); **18,** *J. evarete* (NW126–20); **19,** *J. evarete* (NW84–15); **20,** *J. genoveva*? (= *J. evarete*; NW155–2); **21,** *J. vestina* (no image) (NN07); **22,** *J. vestina* (Las Culebrillas, Cañar, Ecuador; DNA not extracted). Photograph credits: **2, 3, 18–20,** Nymphalidae Systematics Group (2009); **1, 7, 8,** Wain Evans; **11,** Janzen and Hallwachs (2009); **22,** Jean-Claude Petit.

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are also present (Brévignon 2008, 2009).

Although the buckeyes are a well-known and much studied group of nymphalid butterflies, especially with respect to genetic factors involved in evolution and development of eyespots and color patterns (Nijhout 1980; Reed et al. 2007; Monteiro 2008; Kodandaramaiah 2009; Monteiro & Prudic 2010), and the chemical ecology and evolution of hostplant preferences (Bowers 1984; Bowers & Puttick 1989; Bowers & Stamp 1997), the systematics of the *J. evarete* complex has been plagued with uncertainty, with species assignments often questionable and unreliable. The confusion can be traced, at least in part, to the pronounced phenotypic variability in wing maculation and coloration within the genus *Junonia* (Tilden 1971; Hafernik 1982). The apparent loss of type specimens, vague or unknown type localities, and non-standardized use of common names have also added to the taxonomic confusion. Molecular phylogenetic evidence suggests that the ancestor of the *J. evarete* complex probably colonized the New World from Africa or Asia relatively recently, ~2–4 million years ago (Ma) (Kodandaramaiah & Wahlberg 2007), implying that subsequent speciation in this group also is relatively recent. Thus, the possibility for incomplete lineage sorting among diversifying taxa may be high. The many observations of hybridization among phenotypic variants of *Junonia* (Rutkowski 1971; Hafernik 1982) are consistent with this possibility.

In the only comprehensive (worldwide) molecular phylogenetic study conducted to date on *Junonia*, based on 3090 base pairs (bp) from both mitochondrial (cytochrome c oxidase subunit I; COI) and nuclear genes (*wingless* and elongation factor-1α), the three nominal species of the *J. evarete* complex partitioned into two well-supported clades, one comprised of *J. evarete* (Brazil and Guadeloupe) and the other consisting of *J. coenia coenia* (Utah and Tennessee, USA) + *J. genoveva* (Martinique) (Kodandaramaiah & Wahlberg 2007). Because total sample size from the two New World clades was low ($N = 8$), and did not include any populations from western North America (with the exception of a single individual from Utah), the relationships of these previously studied taxa to western populations of *Junonia* remain unclear. We also wished to assess whether molecular data from western populations would provide any additional insights into the results of the hybridization studies of Hafernik (1982) who found high genetic similarity among western taxa.

Given the increase in available COI sequence data for *Junonia* from the DNA barcode initiative (Ratnasingham & Hebert 2007), and the fact that most (633 bp) of the 658 bp barcode region was sequenced by Kodandaramaiah and Wahlberg (2007), we were particularly interested in determining if the barcode segment alone could provide informative characters for inferring phylogenetic relationships and addressing taxonomic uncertainties in *Junonia* from the Americas. DNA barcodes, although sometimes of limited usefulness (Elias et al. 2007; Yassin et al. 2010), have been shown to be highly reliable at species-level identifications within the Lepidoptera in the eastern USA and northwestern Costa Rica, with a success rate of >97% for ~2000 morphologically-defined taxa (Hebert et al. 2003, 2010; Janzen et al. 2005; Hajibabaei et al. 2006). In the present study, we analyzed both new and previously published COI sequences from a total of 85 individuals of New World *Junonia*.

## Materials and Methods

**Sampling.** The new taxa of *Junonia* treated here include (1) *J. coenia grisea* from far western USA (California and southern Oregon) and the Baja California Peninsula, Mexico (type locality: South Pasadena, Los Angeles County, California) (Austin & Emmel 1998); specimens for the present study were collected at a residential development site in Santa Barbara, California, USA, (2) a population from northwestern Mexico that feeds on black mangrove *Avicennia germinans* (L.) L. (Acanthaceae) (Pfeiler 2011). This population is listed as *J. evarete* by Brown et al. (1992) (an assignment initially followed here) and referred to as an intermediate between *J. evarete zonalis* and *J. coenia* by Hafernik (1982); our samples were collected at a mangrove estuary (Estero del Soldado) near San Carlos, Sonora, Mexico, (3) the taxon currently recognized as *J. evarete nigrosuffusa* (Luna-Reyes et al. 2008; Pelham 2008), a large, dark subspecies inhabiting southwestern USA and Mexico, generally inland from the immediate coast (type locality: southeastern Arizona); our specimens were collected in the coastal foothills of the Sierra El Aguaje at San Carlos, Sonora, Mexico. GenBank sequences were available for a population of *Junonia* from the Area de Conservación Guanacaste (ACG), Guanacaste Province in northwestern Costa Rica assigned to *J. evarete*, whose foodplants include *Dyschoriste valeriana* Leonard (Acanthaceae) and *Stachytarpheta jamaicensis* (L.) Vahl (Verbenaceae) (DeVries 1987; D.H. Janzen & M. Hajibabaei unpublished). Additional GenBank sequences were obtained for specimens collected in southern Mexico, Panama, Brazil, Peru, French Guiana, central and eastern USA, and the Caribbean. Details on taxa analyzed, collection data and GenBank accession numbers for the complete data set are given in Table 1.

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TABLE 1. List of species of *Junonia* analyzed for COI, with collection data and GenBank accession numbers.

| Species | Voucher code | Locality | Geographic Coordinates | Altitude (m) | Collection date | GenBank access. no. | Ref [a] |
|---|---|---|---|---|---|---|---|
| *J. coenia coenia* (USA) | NW38–18 | Washington Co. UT | | | 29 May 1998 | AY248777 | 1 |
| (*N* = 6) | NW85–13 | Shelby Co., TN | | | 1992 (reared) | AY788643 | 1 |
| | DNA–ATBI–0802 | Swain Co., NC | 35.520 N, 83.304 W | 607 | 20 July 2004 | GU089962 | 2 |
| | DNA–ATBI–0816 | " | 35.550 N, 83.308 W | | 19 July 2004 | GU089963 | 2 |
| | Bio175–17 | Hart Co., KY | | | | EU271674 | |
| | TDWG-0126 | Barnstable Co., MA | 41.642 N, 70.558 W | 36 | 29 Sept. 2010 | HQ964540 | 6 |
| *J. coenia grisea* ( USA) | CIAD 10–B03 | Santa Barbara, CA | 34.459 N, 119.759 W | 130 | 19 June 2010 | JQ430685 | 3 |
| (*N* = 7) | CIAD 10–B04 | " | " | " | " | JQ430686 | 3 |
| | CIAD 10–B05 | " | " | " | " | JQ430687 | 3 |
| | CIAD 10–B06 | " | " | " | " | JQ430688 | 3 |
| | CIAD 10–B07 | " | " | " | " | JQ430689 | 3 |
| | CIAD 10–B08 | " | " | " | " | JQ430690 | 3 |
| | CIAD 10–B09 | " | " | " | " | JQ430691 | 3 |
| *J. evarete* (Brazil) | NW36–2 | Minaçu, Goiás | | | 1 Dec. 1998 | EU053298 | 1 |
| (*N* = 5) | NW84–15 | Minaçu, Goiás | | | " | EU053299 | 1 |
| | NW126–20 | Acre | | | | EU053295 | 1 |
| | NW129–30 | Acre | | | | EU053296 | 1 |
| | NW151–3 | Vigia, Pará | 0.858 S, 48.142 W | | 19 July 2006 | JQ430732 | 5 |
| *J. evarete* (Guadeloupe) | NW136–17 | Guadeloupe | | | 16 Dec. 2003 | EU053297 | 1 |
| *J. evarete* (Mexico) | CIAD 10–B01 | San Carlos, Sonora | 27.959 N, 110.981 W | <2 | 8 Jan. 2010 | JQ430692 | 3 |
| (*N* = 22) | CIAD 10–B10 | " | " | " | 21 July 2010 | JQ430693 | 3 |
| | CIAD 10–B11 | " | " | " | 16 Aug. 2010 | JQ430694 | 3 |
| | CIAD 10–B12 | " | " | " | " | JQ430695 | 3 |
| | CIAD 10–B13 | " | " | " | 20 Aug. 2010 | JQ430696 | 3 |
| | CIAD 10–B14 | " | " | " | " | JQ430697 | 3 |
| | CIAD 10–B15 | " | " | " | " | JQ430698 | 3 |
| | CIAD 10–B16 | " | " | " | 25 Sept. 2010 | JQ430699 | 3 |
| | CIAD 10–B17 | " | " | " | " | JQ430700 | 3 |
| | CIAD 10–B18 | " | " | " | " | JQ430701 | 3 |
| | CIAD 10–B19 | " | " | " | " | JQ430702 | 3 |

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Table 1. (continued)

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| | CIAD 10–B20 | " | " | " | " | JQ430703 | 3 |
| | CIAD 10–B21 | " | " | " | " | JQ430704 | 3 |
| | CIAD 10–B22 | " | " | " | " | JQ430705 | 3 |
| | CIAD 10–B23 | " | " | " | " | JQ430706 | 3 |
| | CIAD 10–B27 | " | " | " | 11 Oct. 2010 | JQ430707 | 3 |
| | CIAD 10–B28 | " | " | " | " | JQ430708 | 3 |
| | CIAD 10–B29 | " | 27.983 N, 111.043 W | 42 | 1 Nov. 2010 | JQ430709 | 3 |
| | CIAD 10–B37 | " | 27.959 N, 110.981 W | <2 | 9 Nov. 2010 | JQ430710 | 3 |
| | JM6–10 | El Limón, Morelos | | 1200 | 29 June 2007 | JQ430733 | 5 |
| | NW162–7 | Cerro Frio, Morelos | | 1600 | 13 July 2007 | JQ430731 | 5 |
| | MAL–02877 | Tulum Pueblo, QR | 20.146 N, 87.575 W | | 7 Feb. 1993 | JN201293 | 7 |
| *J. e. nigrosuffusa* (Mexico) | CIAD 10–B24 | San Carlos, Sonora | 27.997 N, 111.047 W | 70 | 1 Oct. 2010 | JQ430711 | 3 |
| ($N$ = 10) | CIAD 10–B25 | " | " | " | 8 Oct. 2010 | JQ430712 | 3 |
| | CIAD 10–B26 | " | " | " | 11 Oct. 2010 | JQ430713 | 3 |
| | CIAD 10–B30 | " | 27.983 N, 111.043 W | 42 | 1 Nov. 2010 | JQ430714 | 3 |
| | CIAD 10–B31 | " | " | " | " | JQ430715 | 3 |
| | CIAD 10–B32 | " | " | " | " | JQ430716 | 3 |
| | CIAD 10–B33 | " | " | " | " | JQ430717 | 3 |
| | CIAD 10–B34 | " | 27.997 N, 111.047 W | 70 | 2 Nov. 2010 | JQ430718 | 3 |
| | CIAD 10–B35 | " | 27.968 N, 111.045 W | 30 | 5 Nov. 2010 | JQ430719 | 3 |
| | CIAD 10–B36 | " | " | " | " | JQ430720 | 3 |
| *J. evarete* (Costa Rica) | 03–SRNP–28069 | ACG, Guanacaste | 11.018 N, 85.450 W | 410 | 9 Sept. 2003 | GU334034 | 4 |
| ($N$ = 22) | 03–SRNP–28076 | " | " | " | 5 Sept. 2003 | GU334037 | 4 |
| | 04–SRNP–15110 | " | 10.838 N, 85.619 W | 295 | 31 Oct. 2004 | GU157294 | 4 |
| | 05–SRNP–31184 | " | 11.019 N, 85.410 W | 440 | 23 April 2005 | GU157298 | 4 |
| | 05–SRNP–31186 | " | " | " | 13 April 2005 | GU157295 | 4 |
| | 05–SRNP–31187 | " | " | " | 26 April 2005 | GU157296 | 4 |
| | 05–SRNP–31188 | " | " | " | 27 April 2005 | GU157297 | 4 |

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TABLE 1. (continued)

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| *J. evarete* (Costa Rica) (continued) | 05–SRNP–31215 | " | " | " | 7 April 2005 | GU157299 | 4 |
| | 05–SRNP–57995 | " | 10.767 N, 85.433 W | 325 | 24 July 2005 | GU157288 | 4 |
| | 05–SRNP–57996 | " | " | " | " | GU157285 | 4 |
| | 05–SRNP–57998 | " | " | " | 22 July 2005 | GU157287 | 4 |
| | 05–SRNP–57999 | " | " | " | 23 July 2005 | GU157286 | 4 |
| | 05–SRNP–58001 | " | " | " | " | GU157290 | 4 |
| | 05–SRNP–58009 | " | " | " | " | GU157291 | 4 |
| | 05–SRNP–58011 | " | " | " | 22 July 2005 | GU157280 | 4 |
| | 05–SRNP–58208 | " | 10.768 N, 85.426 W | 480 | 28 July 2005 | GU157292 | 4 |
| | 05–SRNP–58220 | " | " | " | 6 Aug. 2005 | GU157284 | 4 |
| | 05–SRNP–58221 | " | " | " | 29 July 2005 | GU157300 | 4 |
| | 05–SRNP–58241 | " | " | " | " | GU157283 | 4 |
| | 05–SRNP–58257 | " | " | " | 28 July 2005 | GU157282 | 4 |
| | 05–SRNP–58293 | " | " | " | " | GU157289 | 4 |
| | 05–SRNP–32756 | " | 11.019 N, 85.410 W | 440 | 16 Aug. 2005 | GU157281 | 4 |
| *J. evarete* (Panama) | YB-BCI12765 | Barro Colorado Is. | 9.155 N, 79.848 W | 150 | 24 May 2009 | HM416470 | 6 |
| *J. evarete* (French Guiana) | UK4–15 | Montsinéry | | | | JQ430730 | 5 |
| *Junonia* sp. (Fr. Guiana) | UK4–16 | Macouria | | | | JQ430722 | 5 |
| *J. genoveva* (Fr. Guiana) | UK4–14 | Kaw-Roura | | | | JQ430728 | 5 |
| *J. genoveva* (Martinique) | NW136–16 | Les Salines, Sainte-Anne | | | 15 Feb. 2004 | EU053300 | 1 |
| *J. genoveva* (Guadeloupe) | UK4–18 | Port-Louis | | | | JQ430727 | 5 |
| ($N$ = 2) | UK4–19 | Port-Louis | | | | JQ430726 | 5 |
| *J. genoveva*? (Brazil) | NW155–2 | Ubatuba, São Paulo | | | 21 May 2005 | JQ430729 | 5 |
| *Junonia* sp. (Dominican | NW153–11 | Pedernales | | | 8 Nov. 2006 | JQ430725 | 5 |
| (Republic) ($N$ = 3) | NW153–12 | Pedernales | | | " | JQ430724 | 5 |
| | NW153–14 | Hatillo, Azua | | | 9 Nov. 2006 | JQ430723 | 5 |
| *J. vestina* (Peru) | NN07 | near Laguna Huacracocha | | 4000 | 26 Oct. 2009 | JQ430721 | 5 |

[a]References: 1, Kodandaramaiah and Wahlberg (2007); 2, Hebert et al. (2010); 3, this study; 4, Janzen and Hallwachs (2009); 5, Nymphalidae Systematics Group (2009); 6, Ratnasingham and Hebert (2007); Barcode of Life Data System (http://www.barcodinglife.org); 7, Prado et al. (2011).

**Molecular protocol and data analysis.** Total genomic DNA was extracted from two legs of each butterfly using the DNeasy™ (QIAGEN Inc., Valencia, CA) protocol. The polymerase chain reaction (PCR) was used to amplify the barcode segment of the COI gene with primers LCO1490f and HCO2198r using standard PCR conditions (Folmer et al. 1994). Sequencing reactions were performed on an Applied Biosystems (Foster City, CA) ABI 3730XL DNA sequencer at the DNA Sequencing Facility, University of Arizona, Tucson using the amplifying primers. Sequences were proofread and aligned in ClustalX 1.81 (Thompson et al. 1997) followed by manual editing.

Calculations of Kimura (1980) 2–parameter (K2P) genetic distances (*d*) among sequences were carried out in MEGA version 4.0 (Tamura et al. 2007). Calculations of genetic diversity indices and Tajima's (1989) *D* were performed in DnaSP version 5.00.04 (Librado & Rozas 2009). Relative rate tests (Tajima 1993) of sequence evolution were carried out in MEGA using *J. orithya* as the outgroup. Analysis of molecular variance (AMOVA, Excoffier et al. 1992) performed in ARLEQUIN version 3.5.1.3 (Excoffier & Lischer 2010) was used to test for structure among selected populations of *Junonia.* The calculation of significance ($\alpha = 0.05$) of the fixation index $\Phi_{ST}$ was based on 10,000 permutations of the data matrix. Estimates of the number of migrants per generation ($N_m$) among populations were also calculated in ARLEQUIN.

**Phylogenetic analyses.** For phylogenetic analyses all COI sequences were trimmed to 633 bp to correspond to the barcode region reported in Kodandaramaiah and Wahlberg (2007). Relationships among haplotypes were assessed with the neighbor-joining (NJ) algorithm of Saitou and Nei (1987) carried out in MEGA using a matrix of K2P distances. We used two African species of *Junonia* as outgroups, *J. orithya* (GenBank EU053315) and *J. westermanni* (GenBank EU053319). Both African species show a close relationship with the New World *Junonia* (Kodandaramaiah & Wahlberg 2007). *Junonia orithya*, in particular, shares similarities in both wing pattern and morphology of male genitalia with New World *Junonia* (Corbet 1948; Tilden 1971). Statistical support for nodes was obtained by bootstrap analyses using 1000 pseudoreplicates (Felsenstein 1985). Confirmation of clades identified from NJ analysis was obtained by constructing phylogenetic trees with (a) Bayesian inference implemented in MrBayes version 3.1 (Huelsenbeck & Ronquist 2001), sampling 4000 trees and using both HKY and GTR nucleotide substitution models, and (b) maximum parsimony (MP) carried out in MEGA using the CNI heuristic search option and 100 random additions of sequences. Clade support for Bayesian trees was estimated utilizing a Markov chain Monte Carlo (MCMC) algorithm and expressed as posterior probabilities; relative support for MP tree topology was obtained by bootstrapping using 500 pseudoreplicates.

## RESULTS

**Sequence data and genetic diversity.** A complete barcode segment (658 bp) was available for 68 of the 85 individuals of *Junonia* shown in Table 1. No stop codons or indels were found in any of the sequences. There were 53 variable sites. Nucleotide composition was nearly identical in the 68 sequences (mean values: 38.7% T, 14.6% C, 31.4% A and 15.2% G). There was a strong bias against G at the third codon position (mean G content 1.4%; range 0.5–2.7%). Inspection of the 658 bp segment in the 68 samples revealed that of the 53 variable sites, none were present in the first 25 bases that were deleted for phylogenetic analyses.

Genetic diversity indices for *Junonia* are shown in Table 2. Two different patterns were observed. Haplotype diversity ($h$) and nucleotide diversity ($\pi$) were relatively high ($h \geq 0.900$; $\pi > 0.003$) in *J. evarete* from Costa Rica and South America (including the Caribbean) and in *J. coenia coenia* from the USA, but were lower ($h < 0.700$; $\pi < 0.002$) in *J. evarete* and *J. evarete nigrosuffusa* from Sonora, Mexico and in *J. coenia grisea* from southern California, USA. The differences in $h$ and $\pi$ seen in *J. evarete* from Sonora, Mexico and Costa Rica are notable given that sample sizes from the two localities were similar. Tajima's *D* was not significant in any of the taxa. None of the relative rates tests (Tajima 1993) were significant, indicating that a molecular clock could not be rejected for *Junonia.* The AMOVA revealed significant structure among populations of *J. evarete* from Costa Rica ($N = 22$) and Estero del Soldado, Mexico ($N = 19$) ($\Phi_{ST} = 0.398$; $P < 0.0001$). The estimated number of individuals migrating between the two regions per generation ($N_m$) was 0.756. The AMOVA also showed significant structure between the subspecies *J. coenia coenia* ($N = 6$) from eastern USA and *J. coenia grisea* ($N = 7$) from California ($\Phi_{ST} = 0.787$; $P < 0.001$; $N_m = 0.135$).

**Phylogenetic relationships**. Preliminary phylogenetic analyses of the three New World taxa (*J. evarete*, *J. genoveva* and *J. coenia coenia*) from Kodandaramaiah and Wahlberg (2007), using only the 633 bp COI barcode segment and *J. orithya* and *J. westermanni* as outgroups, resolved the *J. evarete* and (*J. coenia* + *J. genoveva*) clades (referred to below as clades A and B, respectively) in NJ, MP and Bayesian trees (not shown) with similar (MP) or identical (Bayesian) clade support

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values reported by those workers from the combined mitochondrial and nuclear data set of 3090 bp.

The NJ tree of New World *Junonia* based on barcodes, and representing both new and previously published data, is shown in Fig. 2. The NJ tree again resolved clades A and B with high statistical support. In addition to the single *J. genoveva* and two *J. coenia coenia* from Kodandaramaiah and Wahlberg (2007), all sequences of *Junonia* from the USA, Mexico, Costa Rica and Panama clustered in clade B, including those from taxa currently assigned to *J. evarete* and *J. evarete nigrosuffusa*. A short COI sequence (290 bp) assigned to *J. evarete* from Quintana Roo, Mexico (Prado et al. 2011) also clustered in clade B (not shown). Within clade B, a weakly-supported subclade consisting of *J. coenia grisea* from southern California was found. All other populations within clade B were unresolved. The same topology, with similar support values, was obtained on a representative subset of sequences from all taxa using MP and Bayesian analyses (not shown).

All populations of *Junonia* from South America and the Caribbean, with the exception of a single *J. genoveva* (= *J. neildi* Brévignon) from Martinique (NW136–16), clustered in Clade A, including individuals identified as *J. evarete* and *J. genoveva*. The resolution of *J. vestina* in a basal position in clade A (referred to here as clade $A_1$) was highly supported. The remaining clade A individuals were all closely related (see below) and are grouped into clade $A_2$.

Pairwise comparisons of K2P genetic distances ($d$) among New World *Junonia* are shown in Table 3. Mean genetic distances were low ($d \leq 1.1\%$) for all comparisons between taxa within clade B. Genetic distance between the subspecies *J. coenia coenia* and *J. coenia grisea* was $d = 1.0\%$. Mean values in all pairwise comparisons between clades A and B, including comparisons with individuals assigned to *J. evarete* which appear in both clades, ranged from $d$ = 4.0–4.5%. These values are higher than the genetic distances found between the two species from Africa used as outgroups, *J. orithya* and *J. westermanni* ($d$ = 3.4%; not shown in Table 3), and also are higher than the value found between *J. orithya* and clade $A_2$ ($d$ = 3.9%); the values are slightly lower than $d$ = 5.0 % found between *J. orithya* and clade B. Within clade A, the genetic distance between the distinctive *J. vestina* (clade $A_1$) and *J. evarete* (clade $A_2$) was $d$ = 2.1 %. The mean value between *J. evarete* from Costa Rica and Sonora, Mexico, localities separated by ~3250 km, was $d$ = 0.5%. Within population $d$ values for *J. evarete* were 0.0–0.5% (mean $d$ = 0.1%) for Sonora and 0.0–1.4% (mean $d$ = 0.5%) for Costa Rica. One individual of *J. evarete* from Sonora shared the same haplotype with an individual from Costa Rica (see Fig. 3).

## DISCUSSION

We have shown that phylogenetic analysis of a 633 bp segment of the mitochondrial COI gene, comprising most of the barcode segment, resolves the two main clades of New World *Junonia* reported previously using a larger data set of both mitochondrial and nuclear genes (Kodandaramaiah & Wahlberg 2007). Barcodes thus provide an informative and relatively inexpensive tool for phylogenetic studies of this group. Assigning individuals of the *J. evarete* complex to their respective clade using morphological characters alone is unreliable and has probably contributed much to the taxonomic

Table 2. Summary of genetic diversity indices and results of neutrality tests (Tajima's $D$) in theCOI gene segment in *Junonia*.

| Species | $N$ | $L$ | $k$ | $K$ | $h$ (± SD) | $\pi$ (± SD) | Tajima's $D$ |
|---|---|---|---|---|---|---|---|
| *J. evarete* (clade $A_2$)* | 12 | 633 | 20 | 10 | 0.970 ± 0.044 | 0.00824 ± 0.00105 | –0.97 |
| *J. evarete* (Costa Rica) | 22 | 658 | 18 | 14 | 0.926 ± 0.039 | 0.00455 ± 0.00075 | –1.45 |
| *J. evarete* (Sonora, Mexico) | 19 | 658 | 3 | 5 | 0.696 ± 0.077 | 0.00133 ± 0.00023 | 0.06 |
| *J. e. nigrosuffusa* (Mexico) | 9 | 658 | 3 | 3 | 0.639 ± 0.126 | 0.00186 ± 0.00042 | 0.41 |
| *J. coenia coenia* (USA) | 5 | 633 | 4 | 4 | 0.900 ± 0.161 | 0.00253 ± 0.00076 | –1.09 |
| *J. coenia grisea* (USA) | 7 | 658 | 2 | 3 | 0.667 ± 0.160 | 0.00116 ± 0.00035 | –0.27 |

$N$, number of sequences; $L$ = sequence length (number of bases); $k$ = number of variable sites; $K$, number of haplotypes; $h$, haplotype diversity; $\pi$, nucleotide diversity. Values for Tajima's $D$ were not significant for any species at the 0.05 level. *All species from South America and the Caribbean clustering in clade $A_2$, including those originally assigned to *J. evarete*, *J. genoveva* or *Junonia* sp. (see Fig. 2), were combined under *J. evarete* in Tables 2 and 3. Five shorter sequences (≤600 bp) from *J. evarete* (clade $A_2$) (NW36–2, UK4–15, UK4–18), *J. e. nigrosuffusa* (CIAD 10–B25) and *J. coenia coenia* (NW38–18) were omitted from Tables 2 and 3.

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TABLE 3. Mean K2P genetic distances (*d*) among taxa and geographic populations of New World *Junonia* based on the COI gene (633 bp). Values for *d* within taxa are shown along the diagonal. Shaded area shows taxa included in clade A, *J. vestina* (clade $A_1$) and *J. evarete* (clade $A_2$) from South America and the Caribbean (see footnote to Table 2). The remaining taxa all cluster in clade B from North America and the Caribbean.

| | | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|---|---|
| 1 | *J. coenia coenia* (USA) (*N* = 5) | 0.003 | | | | | | | |
| 2 | *J. coenia grisea* (USA) (*N* = 7) | 0.010 | 0.001 | | | | | | |
| 3 | *J. e. nigrosuffusa* (MX) (*N* = 9) | 0.003 | 0.010 | 0.002 | | | | | |
| 4 | *J. genoveva* (Martinique) (*N = 1*) | 0.004 | 0.009 | 0.003 | ----- | | | | |
| 5 | *J. evarete* (Sonora, MX) (*N* = 19) | 0.004 | 0.008 | 0.003 | 0.003 | 0.001 | | | |
| 6 | *J. evarete* (Costa Rica) (*N = 22*) | 0.007 | 0.011 | 0.006 | 0.006 | 0.005 | 0.005 | | |
| 7 | *J. evarete* (S. Amer.) (*N* = 12) | 0.043 | 0.043 | 0.042 | 0.045 | 0.044 | 0.042 | 0.008 | |
| 8 | *J. vestina* (Peru) (*N* = 1) | 0.040 | 0.044 | 0.040 | 0.043 | 0.041 | 0.042 | 0.021 | ----- |

confusion. Because of evidence for relatively recent divergences in the New World *Junonia*, however, barcodes alone may be of limited usefulness for inferring intra-clade relationships and species identifications, especially within clade B. All new barcode sequences from populations from western North America, comprising several recognized taxa, clustered in clade B and most showed low genetic divergences ($d < 1\%$). The western *J. coenia grisea*, however, resolved as a weakly-supported subclade within clade B, supporting its designation as a subspecies of *J. coenia* (Austin & Emmel 1998). The AMOVA showed significant population structure among *J. coenia grisea* and *J. coenia coenia*, also consistent with subspecies status. Additionally, our analyses revealed that none of the North American *Junonia* from Mexico and Central America currently recognized as *J. evarete*, including *J. evarete nigrosuffusa* from Mexico, clustered with *J. evarete* from South America and the Caribbean (clade $A_2$). These results suggest that either the taxon currently recognized as *J. evarete* is paraphyletic, or taxonomic assignments of the western populations need to be reconsidered (see below).

Assuming a molecular clock rate of ~2% pairwise sequence divergence per million years for insect COI (Brower 1994; Craft et al. 2010; Pfeiler et al. 2010) we estimate that clades A and B began to diverge ~2.2 Ma. Based on fossil evidence, *Junonia* is thought to have colonized the New World about 2–4 Ma (Kodandaramaiah & Wahlberg 2007). Mean genetic distances between clade A and the outgroup taxa from Africa were 3.9 and 4.3% for *J. orithya* and *J. westermanni*, respectively, suggesting the ancestor of the clade A lineage began to diverge from the African taxa ~2 Ma. Thus, molecular clock considerations and fossil evidence provide estimated dates which are in relatively close agreement, implying that clades A and B began to diverge shortly after colonization of the New World. Because we found no evidence that nucleotide substitution rate in the COI gene in *Junonia* is different from that typically seen in many insects, the low genetic divergences within clade B likely indicate a relatively recent (late Pleistocene or Holocene) radiation and speciation within this group. The low genetic divergences also could result from incomplete lineage sorting and extensive hybridization among diversifying taxa, possibly suggesting just a single, polytypic species. There is evidence, however, apart from the pronounced intra-clade phenotypic variability (Fig. 3), to support recognizing distinct species level taxa within clade B that barcodes are unable to detect.

The low genetic divergences and presumed recent speciation among recognized taxa of *Junonia* comprising clade B are consistent with the conclusions of laboratory hybridization studies showing a high degree of genetic similarity among North and Central American *Junonia* (Hafernik 1982). The taxa used in the hybridization experiments and phenetic analyses of Hafernik (1982) included *J. coenia* (populations from both Texas and California representing what are now recognized as subspecies *J. coenia coenia* and *J. coenia grisea*, respectively), *J. evarete nigrosuffusa* (southern Texas and southeastern Arizona; treated as a full species by Hafernik) and *J. evarete zonalis* (southern Guatemala and northwestern Costa Rica). Caribbean populations, including *J. genoveva*, were excluded from the study [*J. genoveva* is currently listed for southern Texas (Opler et al. 2011; Warren et al. 2011)]. Several lines of circumstantial evidence, however, suggest that the reference populations of *Junonia* from Central America used by Hafernik (1982) may have been from

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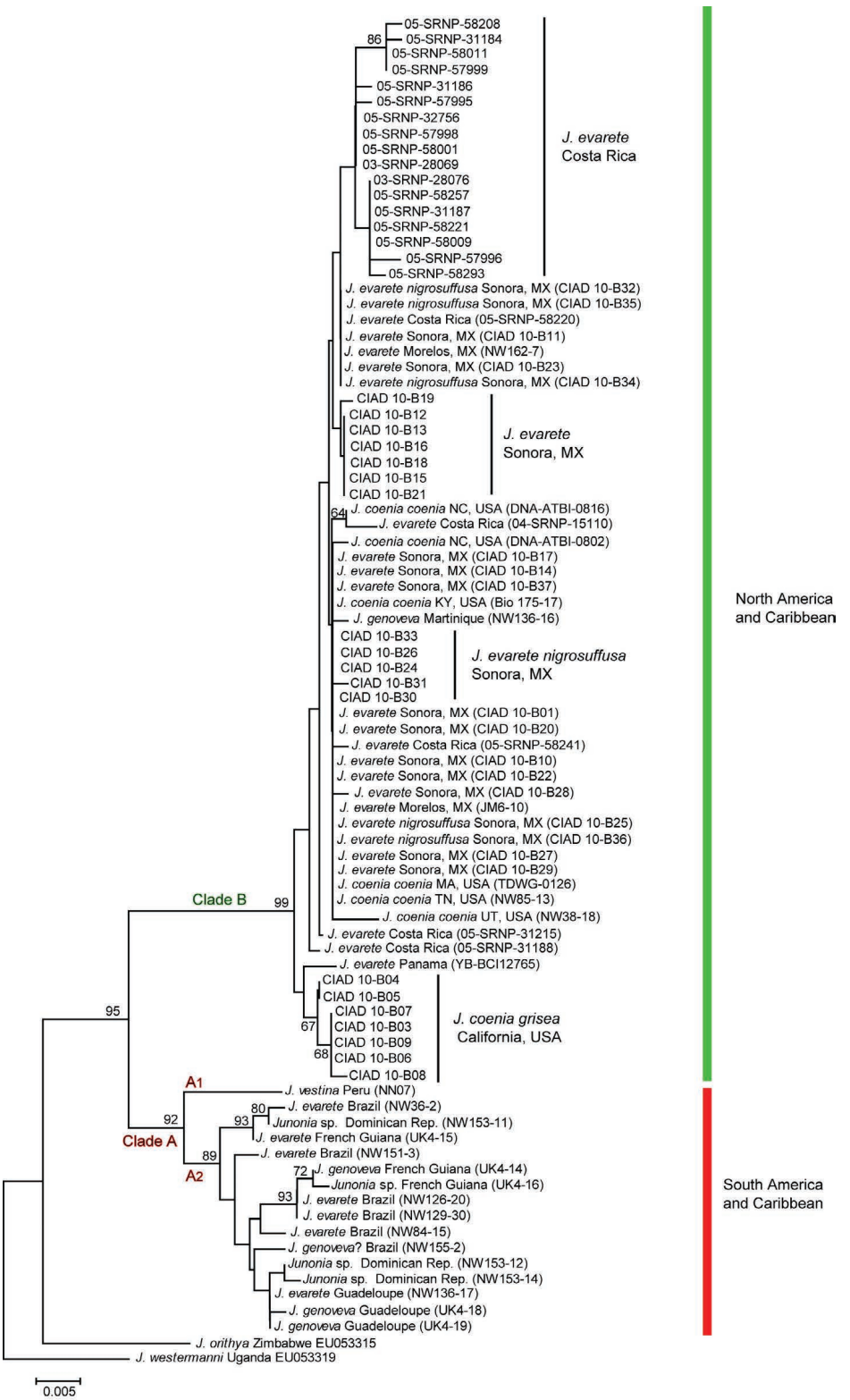



FIG. 2. Neighbor-joining (NJ) tree showing relationships among New World *Junonia* based on COI barcode sequences. Voucher codes are listed for each of the ingroup species (see Table 1 for details). GenBank accession numbers are shown for the outgroups, *J. orithya* and *J. westermanni* from Africa. Red and green bars represent the two main clades (A and B, respectively) of New World *Junonia*. Clade $A_1$ is comprised of *J. vestina*; clades $A_2$ and B contain the members of the *J. evarete* complex. Bootstrap support values are shown on branches; values <60% were omitted. Scale bar indicates sequence divergence.

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the clade B lineage, most probably from the taxon *J. genoveva*. Specimens from these reference populations were taken at Escuintla, Guatemala and Cañas, Costa Rica, both from the Pacific slope and ~700 and ~75 km, respectively, from the Area de Conservación Guanacaste (ACG). Although multiple species of *Junonia* occur in certain regions, no COI genotypes similar to those found in South American and Caribbean populations of *J. evarete* have thus far been detected in the 45 barcode sequences obtained for *Junonia* from the ACG (D.H. Janzen & M. Hajibabaei, unpublished). *Junonia evarete* genotypes also were not present in the two samples from Morelos, Mexico, or in the samples from Quintana Roo, Mexico (Prado et al. 2011) and Panama (Fig. 1). Because of the genetic similarities and lack of reproductive isolation, Hafernik (1982) concluded that *J. evarete nigrosuffusa* and *J. evarete zonalis* represented a cline from Central America to southern Texas and should be considered conspecific. We have shown, however, that *J. evarete nigrosuffusa* from Mexico and *J. evarete* from South America and the Caribbean show a mean genetic divergence ($d$ = 4.2%; Table 3) well within the range of values seen for species level taxa in Lepidoptera based on barcodes (Hajibabaei et al. 2006; Hebert et al. 2010). Finding high genetic identity in hybridization studies between individuals of clades $A_2$ and B would not be expected in two distinct taxa with relatively high genetic divergences. For example, in Jamaica where *J. evarete* and *J. genoveva* both occur, no evidence was found for natural hybridization among the two taxa (Turner & Parnell 1985). However, the conclusions of Hafernik (1982) are consistent with our findings if the Central America taxon used in that study was from the *J. genoveva* lineage and not a subspecies of *J. evarete*. Our argument assumes that *J. evarete* was correctly identified in the earlier molecular study of Kodandaramaiah and Wahlberg (2007). Photographs of *J. evarete* studied by those authors (see Fig. 1) match closely the phenotype of the recently assigned neotype of *J. e. evarete* from Suriname, South America (Neild 2008), suggesting that the identification was correct.

Based on the above arguments we propose that the population of *Junonia* from Mexico that utilizes black mangrove (*Avicennia germinans*) as a larval host, as well as the specimens shown in Table 1 from Morelos

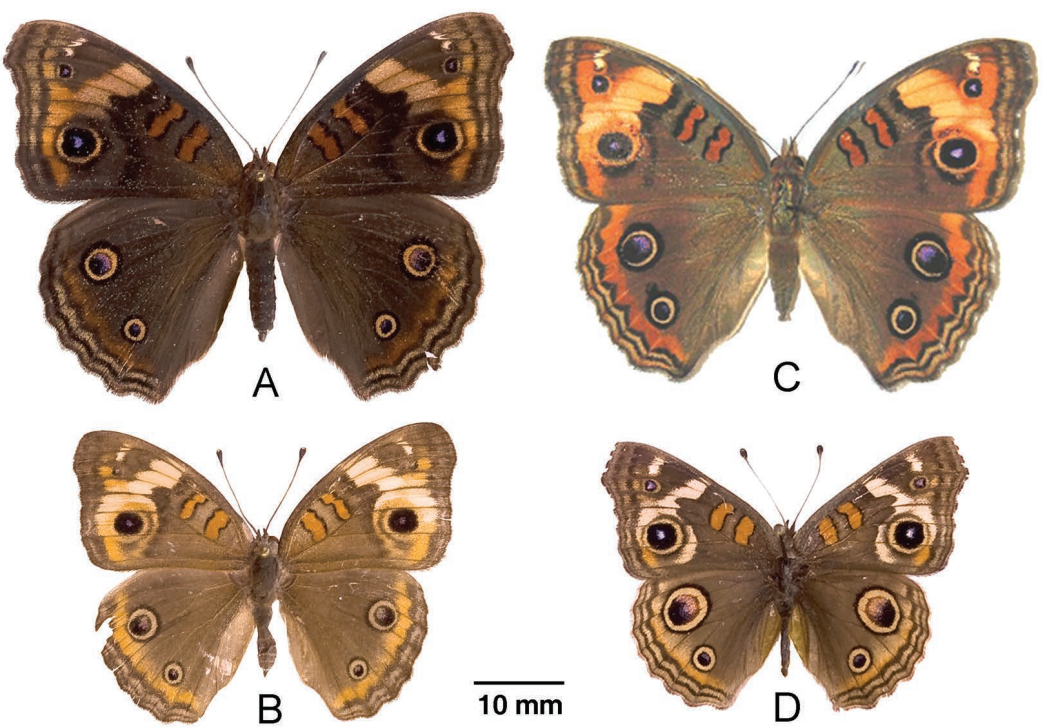



FIG. 3. Comparison of adult females of *Junonia* from western North America showing phenotypic variability. **(A)** *J. evarete nigrosuffusa* (= *J. nigrosuffusa*; see Discussion) (San Carlos, Sonora, Mexico; CIAD 10–B32); **(B)** *J. evarete* (= *J. genoveva*) (Estero del Soldado, near San Carlos, Sonora, Mexico; CIAD 10–B11); **(C)** *J. evarete* (= *J. genoveva*) (Area de Conservación Guanacaste, Guanacaste Province, Costa Rica; 05–SRNP–58220); (D) *J. coenia grisea* (Santa Barbara, California, USA; CIAD 10–B04). Haplotypes for COI were identical for specimens A, B and C; specimen D differs by 5 nucleotide substitutions. Specimens A, B and D are wild-caught; specimen C was reared. Specimen B from Estero del Soldado is a worn individual; ground color of recently eclosed specimens is deep brown (Pfeiler 2011). Scientific names in parentheses are suggested changes in assignment based on data presented here. Photograph credits: **(A), (B)** and **(D),** Wain Evans; **(C),** Janzen and Hallwachs (2009).

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(JM6–10 and NW162–7) and Quintana Roo, Mexico (MAL–02877), Panama (YB-BCI12765), and the population from Costa Rica that utilizes *Dyschoriste valeriana* and *Stachytarpheta jamaicensis*, be removed from *J. evarete* and provisionally reassigned to *J. genoveva*. These new assignments agree with an earlier observation that a possible subspecies of *J. genoveva* occurs in coastal regions of western Mexico (Vargas et al. 1996). Ongoing research on *Junonia* from the Caribbean, however, suggests that the mangrove buckeye probably consists of more than one species, including the recently-named *J. litoralis* Brévignon and *J. neildi* Brévignon (Brévignon 2009). In addition, the clade $A_2$ individual from São Paulo Brazil (Fig. 1, locality 20), was reared on *Avicennia* sp. indicating that representatives of both clades A and B have adapted to feeding on black mangrove. A more thorough examination of relationships among taxa of *Junonia* in the Americas that utilize black mangrove and other host plants may ultimately require revision of our provisional assignment.

Although significant structure was found between the populations of *Junonia* from Estero del Soldado, Mexico and Costa Rica, the low mean genetic distance between the two populations ($d$ = 0.5%) agrees well with intraspecific divergences in Lepidoptera based on barcodes (Hajibabaei et al. 2006; Hebert et al. 2010). Phenotypic differences of adults, however, together with the different host plants utilized by larvae, suggest that these two populations may warrant recognition as distinct subspecies. Also, the higher haplotype and nucleotide diversities of the Costa Rica population compared with the Sonora population (Table 2) suggest that dispersal and colonization proceeded from a southern source population northward along the Pacific slope of North America (Pfeiler et al. 2012). Haplotype and nucleotide diversities were also relatively low in *J. evarete nigrosuffusa* and *J. coenia grisea* (Table 2), but low sample sizes did not allow for unambiguous interpretations of demographic patterns.

The barcode data also suggest that *J. evarete nigrosuffusa* be removed as a subspecies of the *J. evarete* lineage, as it clearly nests within clade B rather than clade $A_2$ (Fig. 2). Two possible alternative assignments, previously proposed by others, are consistent with the genetic data. These include recognizing *nigrosuffusa* as a subspecies of *J. genoveva* (Vargas et al. 1996; Warren et al. 1998; Glassberg 2001), or as a subspecies of *J. coenia* [as originally described by Barnes and McDunnough (1916)]. A third possibility, also previously proposed but supported only by morphological and ecological data, is to recognize the taxon as a full species (Tilden 1971; Emmel & Emmel 1973; Miller & Brown 1981; Bailowitz & Brock 1991; Brown et al. 1992; Brown 2004). In northwestern Mexico, *J. genoveva* and *J. nigrosuffusa* are generally ecologically isolated and morphologically distinct (Fig. 3), with larvae of the two species utilizing different host plants (Tilden 1971; Hafernik 1982; Bailowitz & Brock 1991; Brown et al. 1992; Vargas et al. 1996; Warren et al. 1998; Pfeiler 2011). Our field observations in the San Carlos region of Sonora have revealed no evidence for hybridization, although adults of both lineages are occasionally encountered feeding together (Pfeiler 2011). There are reports, however, of intermediates between the coastal *J. genoveva* and *J. nigrosuffusa* in other regions of western Mexico (Vargas et al. 1996), as well as intermediates between *J. coenia* and *J. nigrosuffusa* from southeastern Arizona (K. Hansen pers. com.). We suggest that, at least for northwestern Mexico, *J. nigrosuffusa* and *J. genoveva* meet the two basic criteria consistent with ecological speciation, i.e. evidence for ecologically-based divergent selection and assortative mating (Chamberlain et al. 2009). Strong adult dispersal capability (Adler & Dudley 1994), together with the ability of larvae to adapt to a variety of host plants from different families, are traits that would favor survival and potentially lead to ecological speciation during the radiation of the New World *Junonia*.

In summary, we have shown that COI barcodes can distinguish *J. vestina* from members of the *J. evarete* complex, and can resolve the two subspecies of *J. coenia*, but overall are of limited usefulness in species identifications within the complex itself. Nonetheless, barcodes are a valuable tool in taxonomic studies of this group for their ability to easily identify the two major clades of the *J. evarete* complex found in the New World, which is difficult, if not impossible, by morphological analysis alone. The ability to unambiguously identify clades A and B will contribute to our understanding of the degree of phenotypic variability and larval host plant preferences within each lineage. More extensive sampling will be required to determine the complete distribution of the two clades in the New World [e.g., records of *J. evarete zonalis* in southern Florida (Warren et al. 2011) suggest the presence of clade A in the USA, and clade B probably occurs South America], but given the widely separated geographic localities in the Americas sampled to date (Fig. 1), it seems unlikely that barcodes will demonstrate additional deep divergences within the *J. evarete* complex. Other molecular markers, however, such as amplified fragment length polymorphisms (AFLPs), show promise of being able to reveal recent divergences that barcodes fail to detect (Dasmahapatra et al. 2010).

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## ACKNOWLEDGEMENTS

We thank W. Evans, T. Hernández Mendoza, A. Martínez, E. Keim, M. Polihronakis Richmond, T. Watts and M. Worobey for their help with this project. We are especially grateful to D. H. Janzen and W. Hallwachs for providing photographs and barcode sequences for Costa Rica specimens, and to J.-C. Petit for permission to use the photograph of *Junonia vestina* from Ecuador. We owe special thanks to N. Wahlberg, A. Freitas and K. Lucas for graciously providing their unpublished sequences of New World *Junonia*. We also thank R. A. Bailowitz, C. Brévignon, J. Calhoun, K. Hansen, and J. A. Scott for their invaluable comments and insights on the systematics and biology of *Junonia*. This research was supported by NSF grant DEB-0346773 to T.A. Markow, a fellowship from the David and Lucile Packard Foundation to M. Worobey at the University of Arizona, Tucson, and funds from the Centro de Investigación en Alimentación y Desarrollo (CIAD), A.C.

## LITERATURE CITED

ADLER, G. H. & R. DUDLEY. 1994. Butterfly biogeography and endemism on tropical Pacific islands. Biol. J. Linn. Soc. 51: 151–162.

AUSTIN, G. T. & J. F. EMMEL. 1998. New subspecies of butterflies (Lepidoptera) from Nevada and California. Pp. 501–522. *In* Emmel, T. C. (ed.), Systematics of western North American butterflies. Mariposa Press, Gainesville, FL.

BAILOWITZ, R. A. & J. P. BROCK. 1991. Butterflies of Southeastern Arizona. Sonoran Arthropod Studies, Inc., Tucson, AZ. 342 pp.

BARNES, W. & J. MCDUNNOUGH. 1916. Some new races and species of North American Lepidoptera. Can. Entomol. 48: 221–226.

BOWERS, M. D. 1984. Iridoid glycosides and host-plant specificity in larvae of the buckeye butterfly, *Junonia coenia* (Nymphalidae). J. Chem. Ecol. 10: 1567–1577.

BOWERS, M. D. & G. M. PUTTICK. 1989. Iridoid glycosides and insect feeding preferences: gypsy moths (*Lymantria dispar*, Lymantriidae) and buckeyes (*Junonia coenia*, Nymphalidae). Ecol. Entomol. 14: 247–256.

BOWERS, M. D. & N. E. STAMP. 1997. Effect of hostplant genotype and predators on iridoid glycoside content of pupae of a specialist insect herbivore, *Junonia coenia* (Nymphalidae). Biochem. Syst. Ecol. 25: 571–580.

BRÉVIGNON, C. 2008. Notes sur les Biblidinae, les Apaturinae et les Nymphalinae de Guyane française (Lepidoptera: Nymphalidae). Lambillionea 108: 3–15.

———. 2009. Nouvelles observations sur le genre *Junonia* en Guyane française (Lepidoptera: Nymphalidae), Première partie. Lambillionea 109: 3–7.

BROWER, A. V. Z. 1994. Rapid morphological radiation and convergence among races of the butterfly *Heliconius erato* inferred from patterns of mitochondrial DNA evolution. Proc. Natl. Acad. Sci. USA 91: 6491–6495.

BROWN, J. W. 2004. Preliminary assessment of Lepidoptera diversity on the Peninsula of Baja California, Mexico, with a list of documented species. Folia Entomol. Mex. 43: 87-114.

BROWN, J. W., H. G. REAL & D. K. FAULKNER. 1992. Butterflies of Baja California. Lepidoptera Research Foundation, Inc., Beverly Hills, CA. 129 pp.

CHAMBERLAIN, N. L., R. I. HILL, D. D. KAPAN, L. E. GILBERT & M. R. KRONFORST. 2009. Polymorphic butterfly reveals the missing link in ecological speciation. Science 326: 847–850.

COMSTOCK, W. P. 1942. *Papilio lavinia* Fabricius and Cramer. J. New York Entomol. Soc. 50: 190–191.

CORBET, A. S. 1948. Papers on Malaysian Rhopalocera. V. The conspecificity of the American *Precis lavinia* (Cramer) with the oriental *P. orithya* (Linnaeus). Entomologist 81: 54–56.

CRAFT, K. J., S. U. PAULS, K. DARROW, S. E. MILLER, P. D. N. HEBERT, L. E. HELGEN, V. NOVOTNY & G. D. WEIBLEN. 2010. Population genetics of ecological communities with DNA barcodes: An example from New Guinea Lepidoptera. Proc. Natl. Acad. Sci. USA 107: 5041–5046.

DASMAHAPATRA, K. K., M. ELIAS, R. I. HILL, J. I. HOFFMAN & J. MALLET. 2010. Mitochondrial DNA barcoding detects some species that are real, and some that are not. Mol. Ecol. Resour. 10: 264–273.

DEVRIES, P. J. 1987. The Butterflies of Costa Rica and their Natural History: Papilionidae, Pieridae, Nymphalidae. Princeton University Press, Princeton, NJ. 327 pp.

ELIAS, M., R. I. HILL, K. R. WILLMOTT, K. K. DASMAHAPATRA, A. V. Z. BROWER, J. MALLET & C. D. JIGGINS. 2007. Limited performance of DNA barcoding in a diverse community of tropical butterflies. Proc. R. Soc. B 274: 2881–2889.

EMMEL, T. C. & J. F. EMMEL. 1973. The butterflies of southern California. Natural History Museum of Los Angeles County, Science Series 26: 1–148.

EXCOFFIER, L. & H. E. L. LISCHER. 2010. Arlequin suite ver. 3.5: A new series of programs to perform population genetics analyses under Linux and Windows. Mol. Ecol. Resour. 10: 564–567.

EXCOFFIER, L., P. E. SMOUSE & J. M. QUATTRO. 1992. Analysis of molecular variance inferred from metric distances among DNA haplotypes: application to human mitochondrial DNA restriction data. Genetics 131: 479–491.

FELSENSTEIN, J. 1985. Confidence limits on phylogenies: An approach using the bootstrap. Evolution 39: 783–791.

FOLMER, O., M. BLACK, W. HOEH, R. LUTZ & R. VRIJENHOEK. 1994. DNA primers for amplification of mitochondrial cytochrome c oxidase subunit I from diverse metazoan invertebrates. Mol. Mar. Biol. Biotech. 3: 294–299.

FORBES, W. T. M. 1928. Variation in *Junonia lavinia* (Lepidoptera, Nymphalidae). J. New York Entomol. Soc. 36: 305–320.

GLASSBERG, J. 2001. Butterflies through Binoculars: The West. Oxford University Press, NY. 374 pp.

HAFERNIK, J. E., Jr. 1982. Phenetics and ecology of hybridization in buckeye butterflies (Lepidoptera: Nymphalidae). Univ. Calif. Pub. Entomol. 96: 1–109.

HAJIBABAEI, M., D. H. JANZEN, J. M. BURNS, W. HALLWACHS & P. D. N. HEBERT. 2006. DNA barcodes distinguish species of tropical Lepidoptera. Proc. Natl. Acad. Sci. USA 103: 968–971.

HEBERT, P. D. N., A. CYWINSKA, S. L. BALL & J. R. DEWAARD. 2003. Biological identifications through DNA barcodes. Proc. R. Soc. B 270: 313–321.

HEBERT, P. D. N., J. R. DEWAARD & J.-F.LANDRY. 2010. DNA barcodes for 1/1000 of the animal kingdom. Biol. Lett. 6: 359–362.

HUELSENBECK, J. P. & F. RONQUIST. 2001. MrBayes: Bayesian inference of phylogeny. Bioinformatics 17: 754–755.

JANZEN, D. H. & W. HALLWACHS. 2009. Dynamic database for an inventory of the macrocaterpillar fauna, and its food plants and parasitoids, of Area de Conservación Guanacaste (ACG), northwestern Costa Rica (SRNP voucher codes) <http://janzen.sas.upenn.edu>. Accessed 22 January 2012.

JANZEN, D. H., M. HAJIBABAEI, J. M. BURNS, W. HALLWACHS, E. REMIGIO & P. D. N. HEBERT. 2005. Wedding biodiversity inventory of a large and complex Lepidoptera fauna with DNA barcoding. Phil. Trans. R. Soc. B 360: 1835–1845.

KIMURA, M. 1980. A simple method for estimating evolutionary rate of base substitutions through comparative studies of nucleotide sequences. J. Mol. Evol. 16: 111–120.

KODANDARAMAIAH, U. 2009. Eyespot evolution: phylogenetic insights from *Junonia* and related butterfly genera (Nymphalidae: Junoniini). Evol. Dev. 11: 489–497.

KODANDARAMAIAH, U. & N. WAHLBERG. 2007. Out-of-Africa origin and dispersal-mediated diversification of the butterfly genus *Junonia* (Nymphalidae: Nymphalinae). J. Evol. Biol. 20: 2181–2191.

LIBRADO, P. & J. ROZAS. 2009. DnaSP v5: A software for comprehensive analysis of DNA polymorphism data. Bioinformatics 25: 1451–1452.

Luna-Reyes, M., J. Llorente-Bousquets & A. Luis-Martínez. 2008. Papilionoidea de la Sierra de Huautla, Morelos y Puebla, México (Insecta: Lepidoptera). Rev. Biol. Trop. 56: 1677–1716.

MILLER, L. D. & F. M. BROWN. 1981. A catalogue/checklist of the butterflies of America north of Mexico. Lepid. Soc. Mem. 2: 1–280.

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MONTEIRO, A. 2008. Alternative models for the evolution of eyespots and of serial homology on lepidopteran wings. BioEssays 30: 358–366.

MONTEIRO, A. & K. L. PRUDIC. 2010. Multiple approaches to study color pattern evolution in butterflies. Tr. Evol. Biol. 2:e2.

NEILD, A. F. E. 2008. The Butterflies of Venezuela. Part 2: Nymphalidae II (Acraeinae, Libytheinae, Nymphalinae, Ithomiinae, Morphinae). Meridian Publications, London. 276 pp.

NIJHOUT, H. F. 1980. Pattern formation on lepidopteran wings: determination of an eyespot. Dev. Biol. 80: 267–274.

NYMPHALIDAE SYSTEMATICS GROUP. 2009. The NSG's voucher specimen database of Nymphalidae butterflies. Version 1.0.15. <http://nymphalidae.utu.fi/db.php>. Accessed 22 January 2012.

OPLER, P. A., K. LOTTS & T. NABERHAUS, coordinators. 2011. Butterflies and Moths of North America. Bozeman, MT: Big Sky Institute. <http://www.butterfliesandmoths.org/>. Accessed 22 January 2012.

PELHAM, J. P. 2008. A catalogue of the butterflies of the United States and Canada. J. Res. Lepid. 40: 1–652.

PFEILER, E. 2011. Confirmation of black mangrove [*Avicennia germinans* (L.) L.] as a larval host for *Junonia genoveva* (Cramer) (Nymphalidae: Nymphalinae) from Sonora, Mexico. J. Lepid. Soc. 65: 187–190.

PFEILER, E., J. E. VERGARA-QUINTANAR, S. CASTREZANA, M. S. CATERINO & T. A. MARKOW. 2010. Phylogenetic relationships of Sonoran Desert cactus beetles in the tribe Hololeptini (Coleoptera: Histeridae: Histerinae), with comments on the taxonomic status of *Iliotona beyeri*. Mol. Phylogenet. Evol. 56: 474–479.

PFEILER, E., S. JOHNSON & T.A. MARKOW. 2012. Insights into population origins of neotropical *Junonia* (Lepidoptera: Nymphalidae: Nymphalinae) based on mitochondrial DNA. Psyche, vol. 2012, Article ID 423756, 6 pp. doi:10.1155/2012/423756.

PRADO, B. R., C. POZO, M. VALDEZ-MORENO & P. D. N. HEBERT. 2011. Beyond the colours: discovering hidden diversity in the Nymphalidae of the Yucatan Peninsula in Mexico through DNA barcoding. PLoS ONE 6(11): e27776. doi: 10.1371/journal.pone.0027776.

RATNASINGHAM, S. & P. D. N. HEBERT. 2007. BOLD: The Barcode of Life Data System (www.barcodinglife.org). Mol. Ecol. Notes 7: 355–364.

REED, R. D., P-H CHEN & H. F. NIJHOUT. 2007. Cryptic variation in butterfly eyespot development: the importance of sample size in gene expression studies. Evol. Dev. 9: 2–9.

RUTKOWSKI, F. 1971. Notes on some south Florida Lepidoptera. J. Lepid. Soc. 25: 137–139.

SAITOU, N. & M. NEI. 1987. The neighbor-joining method: A new method for reconstructing phylogenetic trees. Mol. Biol. Evol. 4: 406–425.

TAJIMA, F. 1989. Statistical method for testing the neutral mutation hypothesis by DNA polymorphism. Genetics 123: 585–595.

———. 1993. Simple methods for testing molecular clock hypothesis. Genetics 135: 599–607.

TAMURA, K., J. DUDLEY, M. NEI & S. KUMAR. 2007. MEGA4: Molecular Evolutionary Genetics Analysis (MEGA) software version 4.0. Mol. Biol. Evol. 24: 1596–1599.

THOMPSON, J. D., T. J. GIBSON, F. PLEWNIAK, F. JEANMOUGIN & D. G. HIGGINS. 1997. The ClustalX windows interface: flexible strategies for multiple sequence alignment aided by quality analysis tools. Nucleic Acids Res. 24: 4876–4882.

TILDEN, J. W. 1971. Comments on the Nearctic members of the genus *Precis* Huebner. J. Res. Lepid. 9: 101–108. ("1970")

TURNER, T. W. & J. R. PARNELL, J.R. 1985. The identification of two species of *Junonia* Hübner (Lepidoptera: Nymphalidae): *J. evarete* and *J. genoveva* in Jamaica. J. Res. Lepid. 24: 142–153.

VARGAS-FERNANDEZ, I., A. LUIS-MARTINEZ, J. LLORENTE-BOUSQUETS & A. D. WARREN. 1996. Butterflies of the state of Jalisco, Mexico. J. Lepid. Soc. 50: 97–138.

WAHLBERG, N., A. V. Z. BROWER & S. NYLIN. 2005. Phylogenetic relationships and historical biogeography of tribes and genera in the subfamily Nymphalinae (Lepidoptera: Nymphalidae). Biol. J. Linn. Soc. 86: 227–251.

WARREN, A. D., I. VARGAS-FERNANDEZ, A. LUIS-MARTINEZ & J. LLORENTE-BOUSQUETS. 1998. Butterflies of the state of Colima, Mexico. J. Lepid. Soc. 52: 40–72.

WARREN, A. D., K. J. DAVIS, N. V. GRISHIN, J. P. PELHAM & E. M. STANGELAND. 2011. Interactive Listing of American Butterflies [22–IV–11] <http://www.butterfliesofamerica.com/>. Accessed 22 January 2012.

YASSIN, A., T. A. MARKOW, A. NARECHANIA, P. M. O'GRADY & R. DESALLE. 2010. The genus *Drosophila* as a model for testing tree- and character-based methods of species identification using DNA barcoding. Mol. Phylogenet. Evol. 57: 509–517.

*Submitted for publication on 15 August 2011; revised and accepted on 24 January 2012.*

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